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PERMAFROST DEGRADATION AND THERMOKARST PROCESSES ASSOCIATED WITH HUMAN-INDUCED DISTURBANCES, FORT NORMAN, N.W.T.

BY

BONNIE JEAN GALLINGER ©

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER
OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA
SPRING 1991

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled:

PERMAFROST DEGRADATION AND THERMOKARST ASSOCIATED WITH HUMAN-INDUCED TERRAIN DISTURBANCE, FORT NORMAN, N.W.T..

Submitted by: Bonnie Jean Gallinger in partial fulfilment of the requirements for the degree of: MASTER OF SCIENCE.

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ABSTRACT

The primary objective of this project was to define and quantify some of the short-term terrain responses to various levels of human disturbance. The nature of the SEEDS site disturbance involved the creation of hand-cleared rights-of-way (ROW) and a simulated buried pipeline trench. The results from the first three thaw seasons form the basis of this thesis.

Controlled disturbances have had an effect on the thickness and rate of thaw of the active layer and on the degree of thermokarst subsidence. In general, all disturbed surfaces had an increased thaw depth and rate relative to the undisturbed control. The degree of alteration to the vegetation canopy and of the organic mat determined the impact on the thermal regime and the consequent degradation of the near-surface permafrost. The greater the degree of disruption the greater the depth of thaw. Considerable variation in thaw characteristics existed within each level of disturbance as well as between them.

The unexpected 46% (18.5 cm) increase in thaw depths under control conditions was attributed to unintentional disturbance and/or regional climatic warming. The irregular topography created by differential settlement of the ROW and control surfaces prevented fluvial erosion. On the ROW, where the understory vegetation and organic mat were left in place, active layer thickening averaged 120% (48.2 cm). Preservation of the insulating organic mat reduced the magnitude and rate of permafrost degradation.

The thickness of the active layer beneath the trenched areas increased by an average of 220% (an increase of 88.5 cm) following removal of the vegetation and organic mat. Thaw subsidence was also maximized (18.9 cm) under the trench conditions. In addition to thermokarst subsidence, the accumulation and channelization of surface water promoted the modification of the trenched areas by both mechanical and fluvio-thermal erosion processes. Degradational slope processes have caused the trench depression to expand laterally beyond its original boundaries. Trench subsidence decreased in 1988 due to the decrease in excess ice with depth. Each level of disturbance experienced a significant increase in thaw depth and rate over the three thaw seasons of observation. Significant differences between the thaw depths/rates of different-aged disturbances were not consistent.

A number of unintentional disturbances, such as footpaths, also resulted in surface disruption and permafrost degradation. As of 1988, the revegetation experiments had no significant impact in slowing the rate of thaw. Insulation treatments, on the other hand, have had a limited retarding effect.

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CHAPTER ONE: LITERATURE REVIEW AND PROJECT OVERVIEW

Introduction

Permafrost is widespread throughout northern regions and, in Canada, it underlies approximately 50% of the land area (Ferrians, 1983). The melting of thaw-susceptible permafrost soils associated with natural or anthropogenic disturbances is responsible for many unique environmental and engineering problems. While the vulnerability of northern soils to surface disturbance is well known by those involved in development, the North is replete with the disrupted terrain associated with human activities.

The dramatic increase in petroleum exploration and development activities during the past few decades has inevitably resulted in a corresponding increase in the number and types of ecosystem/terrain disturbances. Development of these resources requires the construction of producing and processing facilities, as well as an infrastructure of roads, airfields, utility supplies and settlements. The possibility of further resource extraction on a large scale has generated an increased demand for research on the effect of human perturbations on local and regional ecosystems and terrains. The presence of ice-rich permafrost, in addition to seasonal freezing and thawing of the ground raises some special problems. Northern development presents an opportunity for the disruption of the normal thermal regime of the permafrost which can lead to pronounced geomorphic changes such as those produced by frost heaving and the degradation of ground ice (Ferrains et al., 1969; Johnston, 1981).

The recognition of these problems has resulted in an ever-expanding body of literature on the geomorphological and engineering aspects of permafrost in northern ecosystems and the response of the ground-ice to natural and human-induced disturbances (Brown and Grave, 1979; Brown and Pewe, 1973; Gold and Lachenbruch, 1973; Grave, 1983; Heginbottom and Carter, 1989; Lawson, 1986; Mackay, 1970, Strang, 1973; Williams, 1986; among others). Numerous questions, however, remain to be answered before there will be an adequate understanding of the evolution and consequences of terrain disturbances.

Literature Review

Permafrost is defined as a condition below the ground surface, irrespective of texture, water content, or geological character, in which the temperature of the material has remained at or below 0°C for more than two years (Muller, 1947). The mean ground temperature depends upon climatic conditions and energy exchanges between the ground and the atmosphere. The surface energy balance and heat exchange processes are extremely complex and are controlled by both the local and regional climate and the nature of site conditions (soil thermal properties, vegetation characteristics, relief, exposure, etc..) (Brown, 1973, Brown and Pewe, 1973; Gold and Lachenbruch, 1973; Goodwin and Outcalt, 1981).

Detailed microclimatic studies (e.g., Haag and Bliss, 1974a; 1974b; Smith, 1975; Smith and Riseborough, 1983; Rouse, 1984) have resulted in much of what is known about the relationship of discontinuous permafrost to surface conditions. It has been concluded from these studies that differences in microclimate can affect both the annual range in surface temperatures which regulates the active layer characteristics (e.g. temperature, thickness, moisture content) and the mean annual surface temperature which influences the nature of the permafrost. Where ground temperatures are close to 0°C, such as in the subarctic regions, Smith (1975) suggested that the local microclimatic conditions can determine whether permafrost is present or not. Williams (1982), however, suggested that the present state of knowledge makes it difficult to quantitatively assess the significance of the various components of the surface energy budget in maintaining the permafrost condition. Alterations in one or more of these components, associated with surface modification, may lead to changes in the ground thermal regime and initiate permafrost degradation.

The basic cause of permafrost degradation is the disruption of the surface energy budget of ice-rich terrain. In the discontinuous permafrost zone, where the temperature of the permafrost is close to the freezing point, the frozen ground exists in a delicate state of equilibrium with the prevailing environmental conditions, in particular with the amount of incoming solar radiation (Brown, 1963a). In certain areas the permafrost may exist in a disequilibrium with current climatic conditions but is maintained due to micro-scale site characteristics such as thickness of the organic mat, drainage, canopy shading, snow cover and other microclimatic conditions (Brown, 1963b; 1973; Zoltai, 1971). Even relatively minor alterations of these site characteristics can greatly upset this equilibrium, producing changes in the extent, thickness and temperature of the permafrost. In some areas the permafrost is highly vulnerable to deep thawing and will often not regenerate once disturbed (Lachenbruch _et al_., 1966). In regions where the mean annual temperatures are well below 0°C, the changes will likely affect only the upper layer of the permafrost and the depth of the active layer. The active layer being defined as the less stable part, above the permafrost table, where seasonal temperature changes dominate the thermal regime, i.e. where seasonal freezing and thawing occur (French, 1976; Washburn, 1979).

Within the discontinuous permafrost zone, vegetation is one of the most significant factors determining the thickness of the active layer because of its influence on soil heat flux density. The effective thermal barrier provided by moss, lichens, and surface organic layers has been well documented. The thermal properties of these materials vary seasonally: during the summer the surface becomes relatively dry with low thermal conductivity and diffusivity resulting in little cooling of the ground; while in the winter the saturated and frozen surface has a high conductivity and diffusivity which enhances cooling. The overall effect is a negative heat budget with low mean annual temperatures favoring the existence of permafrost (Brown, 1963a, 1973; Luthin and Guymon, 1974; Williams, 1982).

Observations of natural and human-induced surface perturbations and limited experimental data indicate the importance of an insulating layer in preventing permafrost degradation primarily by shielding the underlying soil surface from heat gain during the summer and the subsequent rapid loss of much of the energy that is gained, to the air above (Brown and Johnson, 1965; Brown and Pewe, 1973; Haag and Bliss, 1974a, 1974b; Linell, 1973; Nicholson, 1976; Outcalt and Nelson, 1985; among others). Upon disturbance, the vegetation cover (canopy and ground cover) is, to some degree, removed or compacted thereby reducing the insulating effect of the vegetation and uppermost soil horizons. The ground surface is thus exposed to higher amounts of solar radiation and the consequent increase in the mean annual temperature (Haag and Bliss, 1974a; 1974b; Linell and Johnson, 1973). The increased heat flux and the consequent rise in the mean annual soil temperature will produce an increase in the annual depth of thaw and degradation of the near-surface permafrost (Heginbottom, 1971, 1973; Kerfoot, 1973; Linnel, 1973; Lawson, 1986; Mackay, 1970; Viereck, 1982).

Following surficial disturbance in areas containing high ice content and fine-grained soils, degradation of the permafrost may be expressed on the surface through modification of the microtopography. Mackay (1971; 1977b) stressed that the upper several decimetres of the permafrost tended to be an ice-rich zone easily affected by surface disturbance. Thermomeliation of the active layer and the subsequent loss of volume due to the melting and draining of this ground-ice may result in subsidence and erosion. Recovery and stabilization of disturbed areas have been generally slow and frequently unsatisfactory (Hardy, 1986; Hernandez, 1973; Viereck, 1982; Younkin and Martens, 1985; Younkin and Hettinger, 1978).

The consequences of terrain disturbance may be interrelated and complicated by positive and negative feedback mechanisms leading to long-term environmental and geomorphological disruption as modelled by Mackay (1971), (Table 1.1) French (1976), and Lawson (1986).

In addition to the degradation of the near-surface permafrost, the thermal disequilibrium created by disturbance may lead to thermokarst subsidence, slope instability, and the potential for erosion (Burns and Friele, 1989; Isaacs and Code, 1972; Kerfoot, 1973; Kurfurst, 1973; McRoberts and Morgenstern, 1974; Strang, 1973; Viereck, 1982). The alteration, ponding and concentration of surface runoff can result in changes in the soil thermal regime and subsequent subsidence and fluvio-thermal erosion. (Heginbottom, 1973; Mackay, 1971; Watmore, 1969).

Rationale for research

The primary objectives of this project were to define, evaluate, and quantify some of the short-term physical and thermal changes in the active layer and near-surface permafrost and to the surficial geomorphology following various levels of human disturbance. An anaylsis of the degradational processes that modify the site was also conducted.

Numerous case histories in northern North America have resulted in a general awareness of the sensitivity of permafrost-affected soils to surface disturbance. However, the majority of these studies have been conducted in tundra environments underlain by continuous permafrost (J. Brown et. al., 1969; Chapin and Shaver, 1981; French, 1975; French and Smith, 1980; Lawson et al., 1978; Lawson, 1986). These areas generally have relatively shallow active layers, short thaw seasons and relative structural simplicity in their vegetation (i.e. few layers (strata), low, open canopies). Within the continuous permafrost zone, the thermal regime of the ground is primarily controlled by the regional climate and thus the potential for human-induced thermokarst resulting from surface alterations is reduced (Brown, 1970; French, 1976; Haag, 1973). There is, however, relatively less documentation of disturbances within the Subarctic (discontinuous and sporadic permafrost zones), where the existence and nature (distribution and thickness) of the permafrost is strongly influenced by the vegetation and consequently the degradation and thermokarst induced by the modification or destruction of vegetation may be extensive and long-lasting.

Much of our knowledge of these relationships was obtained during the early 1970's through government- and industry-sponsored terrain and ecological investigations on the potential impacts of oil and gas pipeline projects in the Mackenzie transportation corridor (Heginbottom, 1973; Kerfoot, 1973; Rampton, 1974; Strang, 1973, Zoltai and Pettapiece, 1973). A more complete understanding of the effects of disturbances within the Subarctic will allow for an appraisal of the terrains' sensitivity to development and possibly prevent, or at least minimize, environmental damage in the future.

This thesis will be presented as two separate, but interrelated, papers concerned with the geomorphic impacts of surface disturbances associated with a simulated transport corridor. The first paper deals with the initial phase of thermokarst processes - the characteristics of thaw (thickness and rates) during 3 consecutive thaw seasons. The second deals with the alterations of microtopography resulting from any changes in the thaw layer characteristics. Although portions of this study have been established as long-term, the results of the first three thaw seasons of investigation form the basis for the following two papers.

It was not possible to thoroughly investigate all of the factors involved in terrain disturbance because of logistical, equipment, and time limitations. Rather than approaching this topic from an engineering or geotechnical viewpoint, where the concern is for how terrain factors affect construction and/or other human activities, the approach here will be that of a geomorphic process study with the emphasis on how human-induced changes affected the terrain surface and the active layer. The more complex geotechnical or surface energy budget interpretations and relationships involved in terrain disturbance were beyond the scope of this project.

CHAPTER 2: SITE DESCRIPTION

Investigations were conducted on the Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS) site (64° 58' N., 125° 36' W.), located 10 km north of Fort Norman, Northwest Territories (Figure 2.1). The near-surface permafrost-active layer project was but one component of the ecosystematic studies investigating the effects of human-induced disturbances associated with corridor developments (e.g. pipelines, seismic lines, hydroelectric transmission lines and winter roads) (Kershaw, 1987). The nature of the site disturbance involved the creation of a cleared right-of-way and a simulated buried pipeline trench (Plate 2.1).

The black spruce and larch canopy was hand cleared, over a period of two summers, to create a 25-m-wide right-of-way. The north-south orientated corridors were identified as Rights-of-way (ROW) 1, 2, and 3 (Plate 2.2). ROW 1 and 3 were completed in 1985 while ROW 2 was installed in 1986. ROW 2 and 3 were trenched along their entire length while ROW 1 had a set of four trenched segments with approximately 10 m of buffer between each. The 2-m-wide trench was intended to act as a simulation of a buried pipeline or any surface disturbance resulting in the partial removal of surface organics or excavation and backfilling. Trenching was done to the base of the active layer (an average of 40.4 cm n=134, S.D.=10.3 cm) and then the surface organics, including the moss and lichen layer, were mixed back with the mineral soil

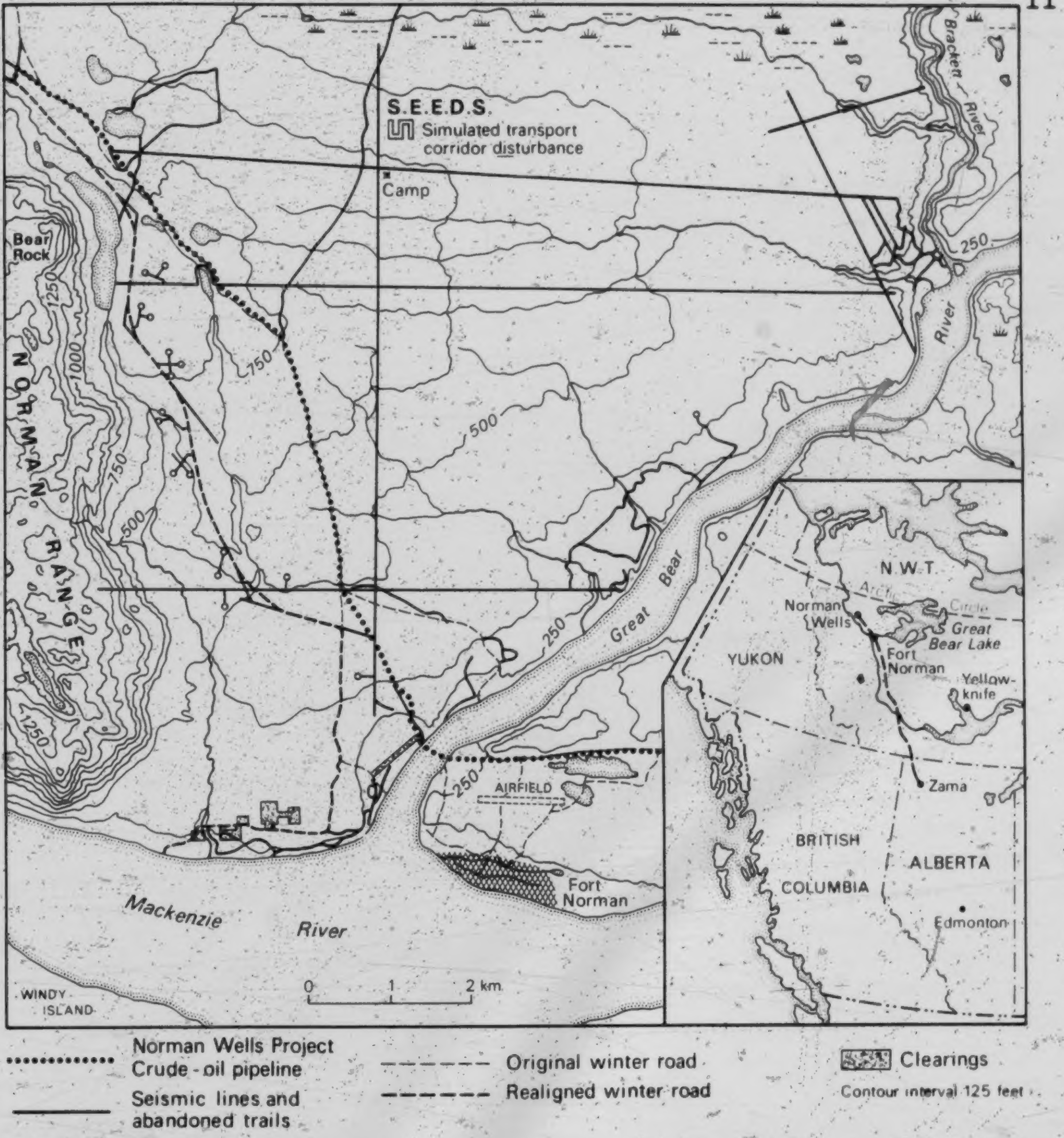

S.E.E.D.S.
Simulated transport corridor disturbance
Camp
Bear Rock
NORMAN RANGE
1250
1000
750
500
250
Great Bear
River
Bracken River
AIRFIELD
Fort Norman
Mackenzie River
WINDY ISLAND
0 1 2 km
N.W.T.
Arctic Circle
Norman Wells
Great Bear Lake
Fort Norman
YUKON
Yellowknife
Zama
BRITISH COLUMBIA
ALBERTA
Edmonton
Norman Wells Project Crude-oil pipeline
Seismic lines and abandoned trails
Original winter road
Realigned winter road
Clearings
Contour interval 125 feet

Figure 2.1. Location of the disturbance installed for the project - Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS). Fort Norman, N.W.T.

Plate 2.1. Southward-facing aerial view of the SEEDS study site (June 1987). ROWs 1, 2, and 3 from left to right. The north-south oriented seismic line on the right side of the photo is typical of the numerous human-induced disturbances in this region.

Plate 2.2 Looking north along ROW 1 showing three of the four trenched segments. Visible on the right side of the photo is the brush pile (windrow) within the control and a footpath that separates the ROW and control.

to be used as backfill. Within the trench, alternating 50 m sections were infilled with slash material prior to the soil backfilling operation (Plate 2.3). The slash was intended to serve as a biodegradable insulative material.

Terrain and regional geology

The terrain has been described as a flat to gently sloping glaciolacustrine and morainal plain with local hummocky micro-relief (IPL, 1980; Reid, 1974). A topographical survey was completed in June 1986 (Figure 2.2). The SEEDS site is situated on a relatively gentle (1.5°), NNE-facing slope, with the highest portion of the site in the southwest with the northeast corner being approximately 6.25 m lower. The lack of a permanent benchmark, on or near the site, prohibited exact elevation determinations. Numerous closed depressions and minor seasonal drainage routes are located randomly throughout the site.

The regional geology consists of Devonian dolomitic and limestone breccias with depths of greater than 5 m to bedrock mantled by unconsolidated Quaternary sediments (Hughes et al., 1973; Reid, 1974). Approximately 10 m of glaciolacustrine and deltaic silts and sands were deposited in the extensive Glacial Lake Mackenzie basin that lined the

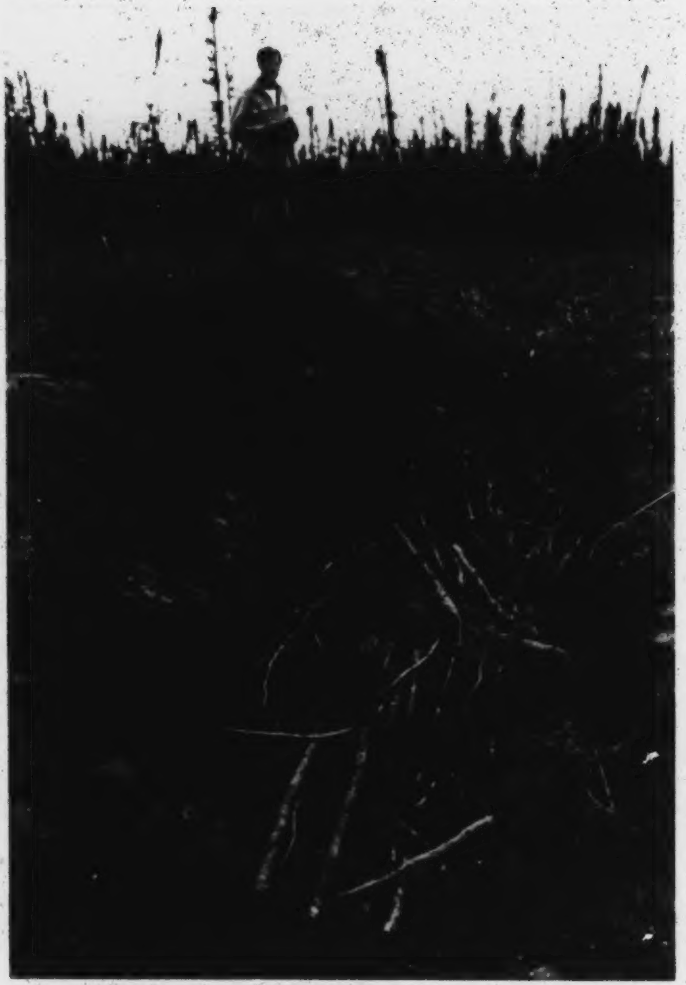
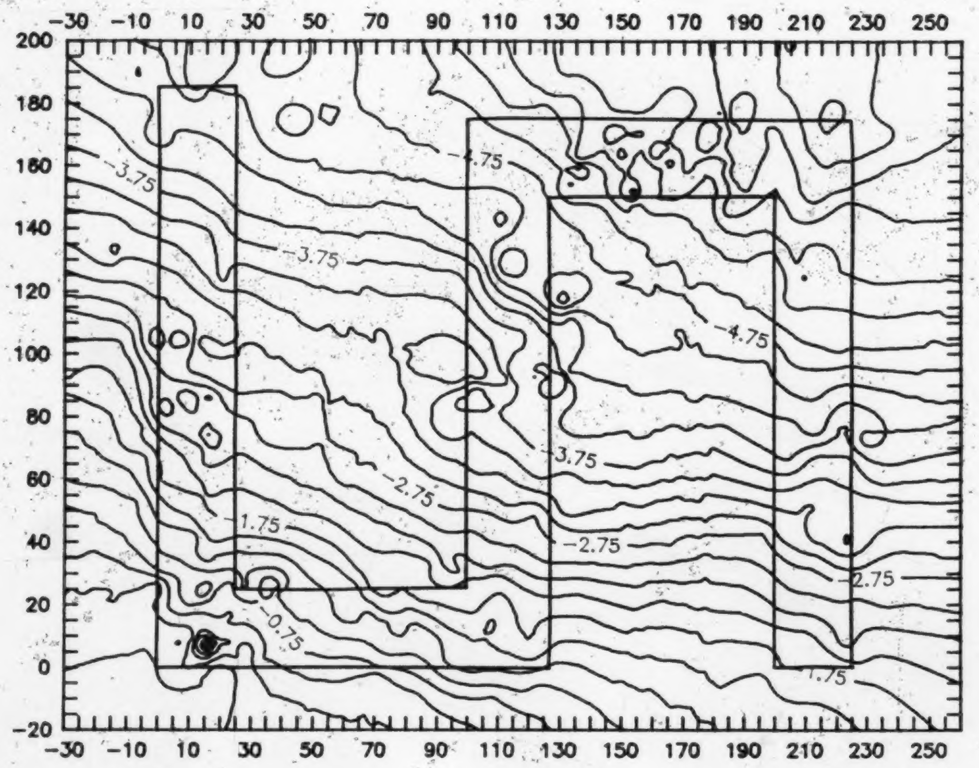


Plate 2.3 Detail of simulated pipeline trench showing one of the trench treatment segements on ROW 1 that was 'insulated' with slash prior to backfilling (July 1985). (Photo credit goes to G.P. Kershaw).


-30
-10
10
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70
90
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190
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230
250
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160
140
120
100
80
60
40
20
0
-20
-3.75
-4.75
-3.75
-4.75
-3.75
-2.75
-1.75
-2.75
-2.75
-0.75
-1.75

Figure 2.2. Detailed topographic map of the SEEDS site. Contour interval is based on 0.25 m deviations from the southwest corner (arbitrary datum point) of ROW 1. Local relief of study site is 6.25 m.

Mackenzie Valley during the close of the Wisconsin glaciations (Smith, 1990). These proglacial lake sediments, with a radiocarbon date of 10,600 B.P. (G.S.C. 2328) for the Fort Norman area, overlie fluted ground moraine and till deposits deposited by the Laurentide ice sheets.

Soils

The soil is classified as a Gleysolic Turbic Cryosol (Canada Soil Survey Committee, 1978; Kershaw and Evans, 1987) with 15 to 30 cm organic soil horizons. The typical soil profile is topped by a moss and lichen layer of approximately 3 to 5 cm in thickness overlying variable thicknesses of moist dark brown forest litter and organics ranging from 15 to 30 cm thick. There is limited A horizon development which, in most cases, grades almost immediately into the frozen and mottled olive-brown parent Cg and Cgz horizons. Soil pits and permafrost cores used for the baseline description of the site (Kershaw and Evans, 1987; Evans et al, 1988) indicated that considerable spatial variation does exist in variables such as particle size, pH, soil moisture as would be expected in a Turbic Cryosol soil (Figure 2.3).

Soils on this lacustrine plain are generally imperfectly drained and moist to wet. The particle size distribution is approximately 25% sand; 55% silt; and 20% clay therefore falling within the silt and clay loam textural classification with low to intermediate plasticity. Below the lacustrine unit is a discontinuous pebble-sized, angular gravel layer at depths ranging between 132 to 225 cm below the ground surface. Coring through this pebble unit was impossible hence its thickness and the nature of the underlying strata are unknown.

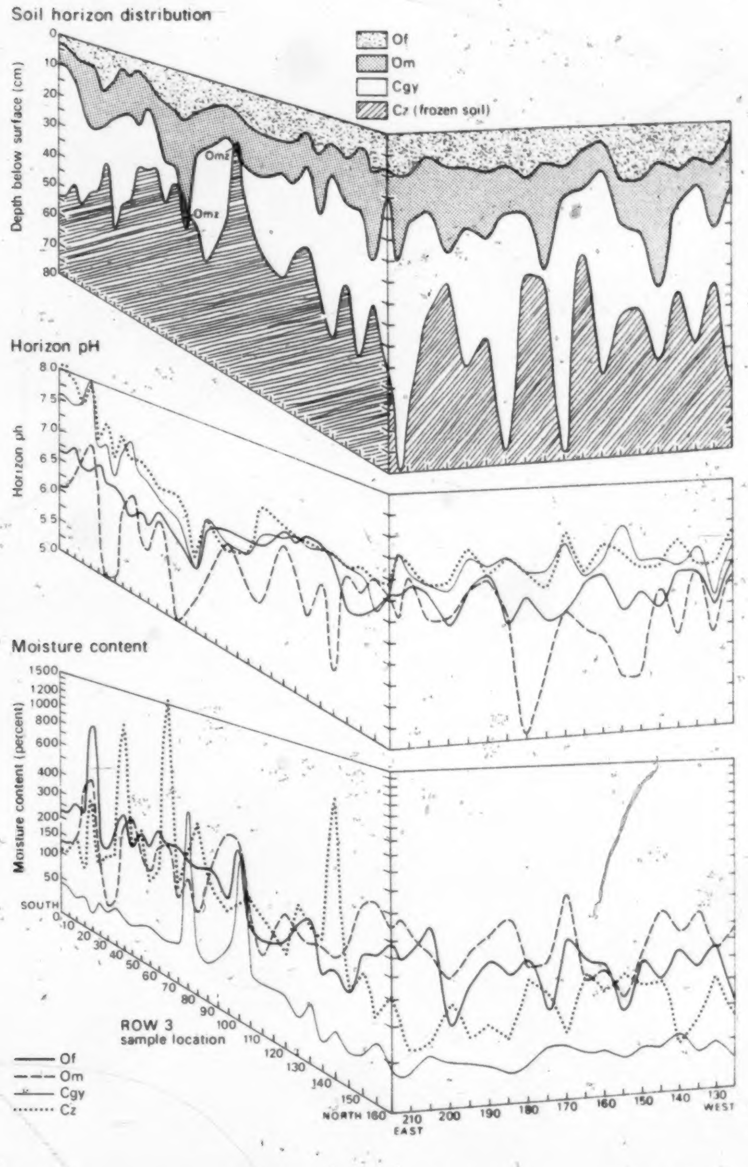


Figure 2.3. Spatial variation of several soil characteristics (soil horizons, pH, and moisture content) along ROW 3 and the north link (Kershaw and Evans, 1987).

Vegetation

The SEEDS site is located within a relatively homogeneous, mature upland subarctic boreal forest community with the dominant tree species being black spruce (Picea mariana) and larch (Larix laricina). The Canadian Ecosystem Working Group (1989) defines the area as being located on or near the boundary between the Low Subarctic and the High Boreal ecoclimatic zones. The open structured canopy of the subarctic boreal forest, at this site, is characterized by single crowns or small clumps of trees with a crown cover density, for trees greater than 2 m in height, of approximately 8% (Kershaw, 1988; Schotte, 1988). The average height of the canopy ranges between 4 and 6 m. While P. mariana, L. laricina, Salix spp. (willow) and Betula spp. (birch) are the dominant species in the tall shrub strata (1 - 2 m), the cover of the understory shrub layer (< 1 m), in descending order, is dominated by Ledum groenlandicum (labrador tea), Arctostaphylos rubra (bear berry), Vaccinium vitis-idaea (lingon berry), Vaccinium uliginosum (billberry), and Empetrum nigrum (crow berry). The ground surface is dominated by an almost continuous layer of non-vascular species including Hylocomnium splendens (feather moss), Tomenthypnum nitens, and Aulacomnium palustre (mosses), and several species of lichens, including Cladonia arbuscula (Kershaw, 1988).

Tree ring counts based on discs indicate that the older black spruce trees within the study site were up to 284 years in age (Kershaw, 1985; 1986). This implies that environmental conditions have been free of disturbances such as wildfires for almost 3 centuries. Conditions of general stability at the ground surface should reflect stable configuration of the permafrost underlying the site (Williams 1982). The relative stability of the site was an important consideration in its selection for disturbance studies. Because the system is assumed to be in equilibrium with the prevailing climate the undisturbed forest can be used as the control, against which subsequent changes on controlled surface disturbances can be compared.

Permafrost conditions

The SEEDS site is located within the discontinuous permafrost zone with underlying permafrost depths locally to 45 m (45 - 76 m at Norman Wells) (Brown, 1969, 1970; Judge, 1973). Nixon et al. (1983) found that approximately 85% of the terrain (150 km south of Norman Wells) is affected by discontinuous permafrost. Boreholes for the Mackenzie gas pipeline, drilled in this region, encountered permafrost in 73% of the holes and 27% encountered excess ice (Templeton Engineering Co., 1973). This is typical of the ice-rich glacial lake deposits found throughout the Mackenzie Valley. How (1974) described the terrain between Fort Norman and Fort

McPherson as being underlain by lacustrine and morainal deposits and having an average excess ice content of 15 to 20%, with local occurrences as high as 50%.

Judge (1973) and Kay et al. (1983) describe the mean annual surface temperatures for the northern portions of the IPL pipeline as ranging between -1°C and -3°C. The permafrost itself is considered as being "warm" with mean annual temperatures ranging approximately from -4°C to -6°C., at the top of the permafrost. Mackay (1975) found the mean annual ground temperature at Fort Norman to be -2°C.

The mean pre-disturbance active layer thickness in the undisturbed forest was 40.3 cm (n=134, S.D.=10.8 based on 1986 data) with local variations in the thickness. Within the first metre of the soil, ice occurs as finely-defined minute crystals, and occasionally as lenses up to several centimeters thick in relatively random orientations (Pemcan in Adams and Hernadez, 1977).

Climate

The climate of the SEEDS area is classified as Continental, with a characteristically large annual temperature range (45°C). The long winters are cold with five months below -20°C while the summers are short with only three months averaging over 10°C (Table 2.1, Figure 2.5). The nearest meteorological station at Fort Norman (10 km south) has a mean annual temperature of -6.2°C (Burns, 1973).

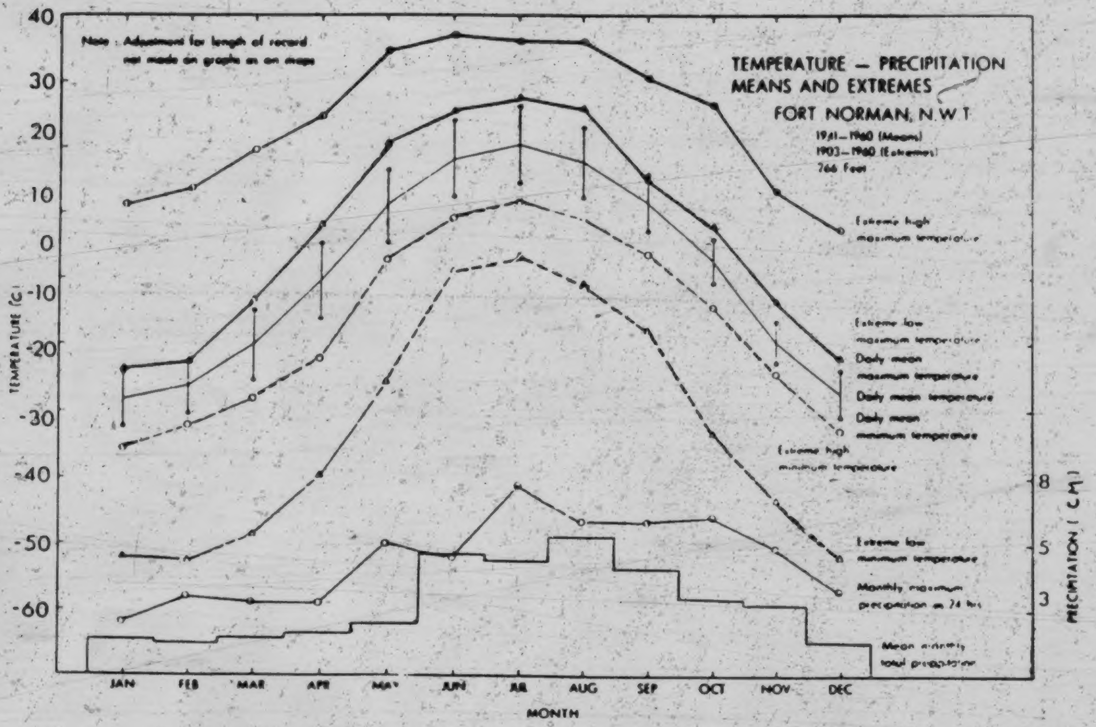
Annual precipitation is relatively low and Atmospheric Environment Service records indicate considerable year-to-year variation in both total precipitation and snowfall. The mean annual precipitation is 469.1 mm with the majority accumulating in winter as light snowfalls. In general, snow cover is present from late October to early May. However, 45 to 55% of the annual total precipitation occurs in the form of intense convective-type rainstorms during the June to September period.

The thaw season, extending from May to September, averages 95 to 125 days in length. The mean annual total growing-degree-days above 5.5°C is 890 while the number of days with frost averages 246 (Table 2.1) (Burns, 1973). The thawing degree day (°C) total for Norman Wells is 1630 while the mean freezing-degree-day total is 4000 (Thompson, 1966).

Table 2.1 Temperature and precipitation means, Fort Norman, Northwest Territories located at latitude 64° 57'N, longitude 125° 00'W, with an elevation of 266' ASL. (source: Canadian Climatic Normals (1951 - 1980) Atmospheric Environment Service).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Mean daily temp (°C)	-28.6	-25.9	-19.4	-7.0	5.3	13.3	16.0	13.3	6.3	-4.4	-18.2	-26.0	-6.3
Mean daily min temp	-31.8	-29.8	-24.3	-13.9	-1.0	6.7	9.1	6.8	1.3	-7.4	-21.0	-29.9	-11.3
Mean daily max temp	-23.1	-21.0	-12.7	-13.3	11.4	19.6	22.1	18.8	10.7	-0.2	-14.2	-22.4	-1.0
Mean monthly precip.	1.39	1.17	1.53	1.44	2.36	4.75	4.63	5.06	3.05	3.51	2.20	1.42	32.49
Mean monthly snowfall	14.7	12.6	16.2	12.1	11.1	1.8	0.00	0.00	5.9	32.7	22.7	14.6	144.3
No. days with frost	31	28	31	30	18	2	1	3	12	29	30	31	246

Figure 2.5. Temperature and precipitation means and extremes, Fort Norman, Northwest Territories. (after Burns, 1973).



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CHAPTER 3:

PERMAFROST DEGRADATION AND ACTIVE LAYER MODIFICATION

INTRODUCTION

Degradation of the permafrost occurs when the mean annual ground temperature rises above 0°C. Disruption of the ground thermal regime and the subsequent thickening of the active layer may be induced by short-term climate oscillations, broad climatic changes or surface disturbances (Mackay, 1971; Rouse, 1982; Smith and Riseborough, 1983; Smith, 1975, 1984). While climatic warming would result in permafrost degradation at a regional scale, localized thermokarst tends to be the result of vegetation disruption or surficial geomorphological disturbances.

There is little doubt that the western Arctic is destined to become a major oil and gas producing area as a partial solution to the escalating energy requirements of the North American continent. The activities associated with resource development and exploration in the Subarctic are likely to continue and possibly increase in number and type. Many of these activities will inevitably lead to the destruction of the natural vegetation cover that serves as insulation for the underlying permafrost. Many studies in the past have shown that disturbances of the environmental equilibrium in northern areas are bound to cause an acceleration of some morphological processes. For an equilibrium, once disturbed, its recovery proceeds at a much slower rate than in other climatic zones.

Knowledge of the rate and extent of permafrost degradation is an important consideration in northern development and engineering projects. The understanding of the evolution of active layer modifications immediately after the initiation of the disturbance could be a primary step in the mitigation of damage to thaw-sensitive terrain (Nelson and Outcalt, 1982). Because alteration of the active layer and near-surface permafrost may affect soil temperature, stability and drainage it may have substantial consequences for other research projects at the SEEDS site such as surface hydrology, revegetation, oil spills, plant vigour and productivity. Therefore this study also serves as a baseline description for such projects where the knowledge of terrain impact is essential.

This first paper will deal with the initial phase of thermokarst processes resulting from human-induced disturbances, specifically the impact on the thickness of the active layer and the degradation of the near-surface permafrost. This is based on the theory that the physical response differs according to the degree that the thermal regime of the affected area is altered by each disturbance type (Haag and Bliss, 1974a, 1974b; Heginbottom, 1973, 1974; Lawson, 1982, 1986). A modified thermal regime can be interpreted through the use of depth of thaw measurements in disturbed and equivalent undisturbed areas. Micro- and meso-scale spatial variations and short-term temporal variations in thaw depth and thaw rates will also be examined.

It has generally been observed that the reaction of the terrain to disturbance depends on a number of factors including the specific nature and intensity of the development activities being undertaken, the time since disturbance and most importantly, the properties of the terrain itself (Heginbottom, 1973; Kurfurst, 1973; Brown and Grave, 1979; Lawson, 1982; 1986; Zoltai and Woo, 1978).

The design of the SEEDS site allows for the comparison of several different levels of terrain disturbance. Most research to date indicates that the greater the degree or severity of disturbance on permafrost terrain, the greater the amount of permafrost degradation. However, variation in the intensity of the original disturbance is not the only factor that controls the reaction of the terrain to disturbance. The physical properties of the terrain itself, including ice/moisture content, grain size, sediment type, slope and aspect, drainage, vegetation, etc., are at least as important. Another significant contributing factor is the time of year of disturbance. The relatively homogeneous terrain conditions of the SEEDS site and the fact that the disturbances were conducted early in the thaw season (May/June) place well-defined boundaries on site and temporal factors, thus permitting the definition and measurement of terrain response based only on the severity of the initial modification and the age of the disturbance.

The undisturbed Picea mariana /feathermoss-Cladonia community serves as the 'control' for this study. Control data serves as baseline information defining the natural variability of the parameters in question against which changes associated with the disturbance can be compared. Comparisons of the nature of the active layer, thaw depth and rate, in the adjacent disturbed and undisturbed sites provided a measure of the degradation of the permafrost resulting from the alteration of the vegetation and ground surface.

A temporal aspect of the effect of environmental manipulation was also investigated. Because the right-of-way clearings and trench installation were completed over a period of two years it can be determined if the length of time since disturbance installation had any significant influence over thaw depths and rates. The removal of the vegetation cover and the trenching of ROW's 1 and 3 took place in 1985 while ROW 2 was installed in May 1986, thus providing 1, 2, 3 and 4 post-disturbance thaw seasons for investigation.

OBJECTIVES AND HYPOTHESES

In order to evaluate the impacts of disturbance on thaw-susceptible terrain the following major objectives were formulated. These objectives were statistically tested using a number of null hypotheses.

Objective 1:
To determine if the intensity of the original disturbance affects the mean thaw depth and rates.

HO1 No significant differences exist in **(A)** the active layer thickness, and **(B)** the rates of thaw among the undisturbed control areas, rights-of-way, and a simulated pipeline trench as a result of human-induced perturbations.

Objective 2:
To determine if the mean thaw depth and thaw rate in each individual disturbance level varies over time.

HO2 No significant differences exist in **(A)** the active layer thicknesses, and **(B)** rates of thaw of the control, rights-of-way, and the trench over the three seasons of thaw.

Objective 3:
To determine if the length of time since the original disturbance had any significant effect on the thaw depths and rates.

HO3 No significant differences exist in **(A)** the active layer thicknesses, and **(B)** rates of thaw associated with surface disturbances of different ages.

Objective 4:
To determine the effect of insulation and revegetation treatments on trench thaw depths.

The various treatments (insulation and revegetation trials) conducted on the simulated pipeline trench will have no effect on the thaw depth.

FIELD AND LAB PROCEDURES

THAW DEPTH AND THAW RATE DETERMINATION

Quantitative information on the thermal regime, or more specifically, on the position of the 0°C isotherm, was collected by two different methods: frost probes and frost tubes.

(1) Frost probes

The seasonal progression of active layer thickening was monitored throughout the summers of 1986, 1987 and 1988. Four parallel frost probe transects were established across the study site in May 1986 (Figure 3.1). Each transect, comprised of 84 sample sites, extended 290 m through the undisturbed control areas; the three minimally disturbed, hand-cleared rights-of-way and the severely disturbed, trenched and backfilled areas. The disproportionate areal extent of the three tupes of disturbances required the use of a stratified sampling regime in order to obtain sufficient data from each level for statistical purposes (Norcliffe, 1977; Ebdon, 1985). The control sample sites were located at 10 m intervals, 2.5 m on the ROW, and 0.5 m on the trench along 4 parallel transects 20 m apart. In the transition zones between the control and ROW the sampling interval was 5 m, and along the edge between the ROW and trench the interval was 0.5 m.

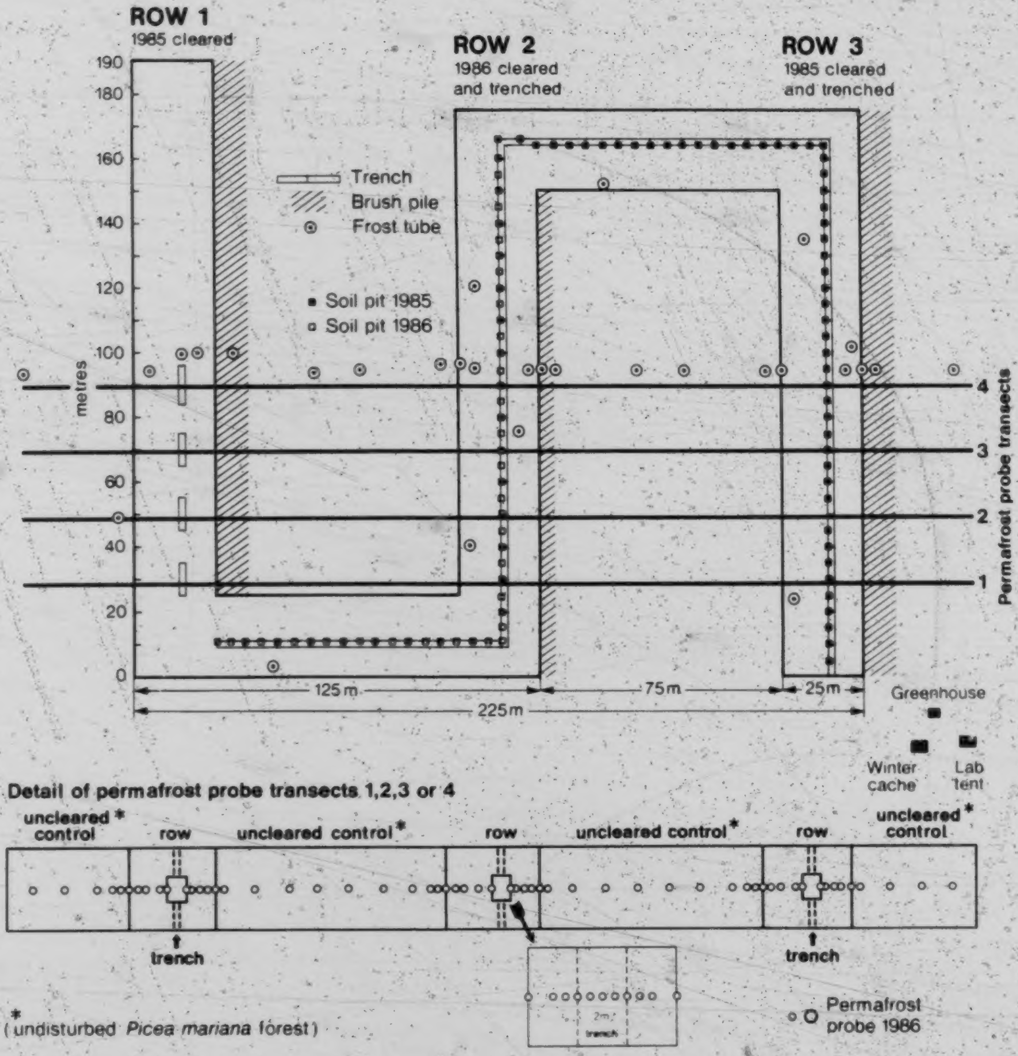

ROW 1
1985 cleared
ROW 2
1986 cleared and trenched
ROW 3
1985 cleared and trenched
190
180
160
140
120
100
80
60
40
20
0
metres
Trench
Brush pile
Frost tube
Soil pit 1985
Soil pit 1986
4
3
2
1
Permafrost probe transects
125 m
75 m
25 m
225 m
Greenhouse
Winter cache
Lab tent
Detail of permafrost probe transects 1,2,3 or 4
uncleared* control
row
uncleared control*
uncleared control*
row
uncleared* control
trench
trench
2m trench
Permafrost probe 1986
*(undisturbed Picea mariana forest)

Figure 3.1 Map of the four permafrost probe transects (with individual sampling sites shown in detail inset) and frost tube locations, SEEDS site.

Reconnaissance probe trials indicated that minor (e.g. 2 cm) shifts in the probe location could result in substantial differences in thaw depths (0-15 cm). Several authors (Gill, 1974; Viereck, 1965; Zoltai and Tarnocai, 1975) acknowledge the importance of how, on a microscale, even small variations in relief and plant cover can influence the distribution of permafrost and the thickness of the active layer. For this reason it was important to probe the exact same location each week. Probe locations were marked with numbered survey pins and after a few weeks the probe holes were easily located through sight or feel.

Thaw depth measurements were determined by hand probing from the moss/organic surface to the top of the seasonal frost table using a graduated (1 cm) aluminum rod, 1 cm in diameter. Arrival at the study site and snow cover conditions determined the timing of the first thaw depth measurement. Thaw depth monitoring took place at weekly intervals from May to September, 1986, 1987 and periodically through the 1988 field season.

The frost probe penetrates to the position of an ice-cemented layer of considerable mechanical strength which may or may not correspond to the 0°C isotherm. Mackay (1977a) expressed concerns that the depth at which resistance to probing is encountered may not necessarily correspond with the position of the 0°C isotherm. Nelson and Outcalt (1982), warn that an overestimation of the position of 'frozen' ground may occur when the upper portion of the frost table (being close to 0°C) may have a large portion of unfrozen pore water at slightly negative temperatures making it less "resistant" to the probe although technically frozen. In response to these concerns, a series of probe depth observations were conducted with a thermocouple attatched to the tip of the probe. Calibration by means of the thermocouple ensured that the point of rod refusal was 0°C (± 0.5°C). However, in the discontinuous permafrost zone, the zero curtain effect at the permafrost table will introduce variability and error regardless of the method used to determine the thaw depth (Rouse, 1982). The probe data, therefore, should be regarded as only an approximation of the 0°C isotherm position. Because any bias associated with the measurement technique remained constant throughout the study, comparisons of the results can be considered valid.

(2) Frost tubes

Because it was not always possible to use the frost probes for determining the position of the 0°C isotherm, frost tubes were also employed (Rickard and Brown, 1972; Viereck and Lev, 1983). Frost probes provide a means of visually determining the position of the freezing front in freezing and thawing soils. The frost tubes, unlike the frost probes, can be used to monitor the fall freezeback process, which proceeds from both the ground surface downward and the permafrost table up.

The frost tubes were constructed in the field according to design specifications of Viereck and Lev (1983). They consist of an outer polyethylene tube that is permanently installed in the soil and an inner, removable acrylic tube which contains a fluoresein-saturated sand mixture. The fluoresein dye changes colour from green to pale orange upon freezing. The colour changes in the tube correspond closely to the phase changes in the porewater of the adjacent soils at similar depths. Conventional soil temperature data and frost probe data have been well correlated with frost tube readings, generally within 1 to 2 cm (Rickard and Brown, 1972).

Extreme care was taken to keep disturbance of the vegetation and ground surface to a minimum while augering the holes and installing the frost tubes. Installation was completed in June 1986. A frost tube transect was established, running parallel to the frost probe lines (Figure 3.5). Ten additional tubes were associated with the rights-of-way sites of microtopography monitoring. These 'bedstead' stations will be discussed in the following paper. The placement of tubes in association with the trench bedsteads proved to be unsuccessful as coring in the trench proved difficult due to the saturated condition of the sediments. An adjustment period of several months was required following the installation of the frost tubes so the ground thermal equilibrium that had been disrupted during the coring procedure could be re-established.

The initial monitoring of the frost tubes was during the November 1986 and 1987 and the February 1987 and 1988 field excursions. During the 1987 summer field season monitoring of each frost tube was on a weekly basis until tubes was completely thawed. Observations were less frequent in July and early August but in mid-August readings were resumed in order to record the intial stages in the freezeback process.

(3) Near-surface soil and air temperatures

Microclimate studies were initiated at the SEEDS site in the winter of 1984 and the summer of 1985 (Kershaw, 1987). A number of automated microloggers continuously compiled data of soil temperatures (0 to >200 cm), air temperatures, global and net radiation, precipitation etc. The original intention of this project was the comparison of the ground temperature regimes (accumulated soil degree days and ground temperature envelopes) with alterations in the active layer and near-surface permafrost associated with the different levels of disturbance. However, the subsequent unavailability of the microclimate data due to periodic equipment malfunction (creating significant data gaps), and the incomplete analysis of the existing data has prevented such interpretation.

Viereck and Lev (1983) have noted that a linear relationship exists between thaw depth and the accumulated thaw index. This relationship is useful in predicting the thawing depth of frozen ground. The index is based on the number of thawing degree days which are defined as the difference between the mean daily temperature and 0°C, when thawing degree days > 0°C. The annual variation in temperatures from one summer to the next (e.g. cool summer v.s. hot summer) prohibit the use of temperature comparisons based on calendar dates alone. Thaw depth was to be compared with the accumulated thaw degree days for each disturbance level, however, only regional data were available. Thaw degree day data were derived from Norman Wells and Fort Norman data (Atmosphere and Environment Services, 1986 - 1988).

SOIL ANALYSIS

A number of other site characteristics were considered to be important in influencing the thaw depth. Permafrost cores were used to describe the moisture and grain size characteristics of the soil, active layer and the near-surface permafrost. A general description of the study site soil conditions was based on soil samples from throughout the site. Cores were taken from different locations across the site: 28 were associated with the frost tube transects, and 28 with the bedstead monitoring stations. Permafrost coring was done by hand to depths of 2 to 2.25 m to where the discontinuous gravel layer generally prevented further penetration. Soil samples were collected from 15 cm intervals down the core.

Quantitative analysis of ice content and form could not be undertaken due to the hand coring procedures which resulted in substantial melting of the outer core sample. Lack of refrigeration facilities prevented the maintenance of frozen core samples for later laboratory analysis. Because of these major limitations, the assesement of ice content was primarily qualitative in nature based on visual inspection during the coring procedure (with the exception of bulk density ice volume measurements). When possible, ground ice was described based on the morphological classification scheme (Table 3.2) developed by Pihlainen and Johnston (1963) and Linell and Kaplar (1966).

Table 3.2. Ground ice description used in North America (after Pihlainen and Johnson, 1963; Linell and Kaplar, 1966).

Group	Symbol	Description	Symbol	Comment
No ice visible	N	Poorly bonded or friable	Nf	Allow sample to warm in jar to estimate quantity of ice. Watch for ice coatings and reflective crystals.
		No excess ice	Nbn	
		Well-bonded excess ice	Nbe	
Visible ice < 2.5 cm thick	V	Individual ice crystals or inclusions	Vx	Describe ice phase using: Location Size Orientation Shape Thickness Pattern and Length arrangement Spacing Hardness Structure Colour Volume of ice
		Ice coatings on particles	Vc	
		Random or irregularly-oriented ice	Vr	
		Stratified or distinctly-oriented ice	Vs	
Ice > 2.5 cm thick	ICE	Ice with soil inclusions	ICE + Soil	Describe as ICE, qualified as to hardness, colour, structure and inclusions.
		Ice without soil inclusions	ICE	

In the field the core samples were bagged, thawed and air dried. Following laboratory oven drying (125°C for 24 hours) the moisture content (Pw) was determined and expressed as a percentage of the final dry weight.

$$Pw = \frac{(\text{wgt of moist soil- wgt of oven-dried soil})}{\text{oven-dried wght of soil}} \text{ X } 100 \tag{1}$$

Ice content, expressed as the percentage of ice by volume, was estimated through bulk density samples. The samples were collected in conjunction with the soil pit investigations (Evans, 1986) and all samples are from the Cg and Cgz soil horizons (25 - 50 cm depth). Samples were taken during the trenching process shortly following canopy removal and therefore should reflect pre-disturbance conditions. The calculation of bulk density measurements allows for the conversion of moisture data from a weight basis to a volumetric basis (Pv).

$$Pv = Pw \times Dbm \tag{2}$$

where: Pw - water content (%) weight basis
Dbm- bulk density of sample g/cm^3

Using the bulk density values the percentage ice by volume was also calculated, as outlined by McKeague (1978):

$$Pv\ (ice) = \frac{(wgt\ of\ wet\ soil - wgt\ of\ dry\ soil)}{volume\ of\ frozen\ soil} \times 108.3 \tag{3}$$

Standard laboratory analyses of grain size distribution was conducted using sieves and the hydrometer method (McKeague, 1978). Due to time constraints and the relative homogeneity of the soil only a portion of the core samples were analyzed.

Along with grain size analysis, plastic and liquid limits testing was conducted for frost/thaw susceptibility determination. Standard Atterberg procedures (McKeague, 1978) were followed using fines less than 420 microns (those passing through the #40 sieve). Using the Casagrande apparatus twenty samples were tested to determine their liquid limits.

An additional source of information regarding soil conditions (including classification, texture, and organic and moisture contents) was obtained from previous soil pit excavations along the simulated pipeline trench (Kershaw and Evans, 1987).

The soils were tested for frost/thaw susceptibility based on the widely accepted criteria first set out by Casagrande (1932) and later adopted by the United States Corp of Engineers. The frost susceptibility index is based on soil grain size characteristics and Atterberg limits. Casagrande concluded that "under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than 3% of grains smaller than 0.02 mm, and in very uniform soils containg more than 10% smaller than 0.02 mm." These criteria, although simple, are still the most widely used and successful for predicting frost susceptibility of soils (Chamberlain, 1981).

DATA ANALYSIS

Analyses for this study were completed using the Lotus 123 and the Statgraphics software programs. Initial investigations showed the frequency distributions of the thaw depth and thaw rate data to be skewed. In order to utilize these data for parametric statistical evaluation they first had to be logarithmically transformed to meet the normality requirements for analysis of variance testing (ANOVA) (Ebdon, 1985; Norcliffe, 1977). Difference of means tests (t-tests) were employed to compare thaw rates and depths among the individual disturbances and years. The F test was substituted whenever there were substantial differences in the n sizes and/or the variances of the two samples.

THAW RATE AND PROGRESSION ANAYLSIS

The rate of thaw is determined using the delta thaw values (maximum minus minimum thaw depth) divided by the number of days of observation and is commonly expressed as $\text{cm}\cdot\text{d}^{-1}$. Jahn (1985), based on observations on the depth of summer thaw in Greenland during the 1940's, noted that the increase in the thickness of the active was approximately proportional to the square root of time. This principle is more clearly defined by Terazghis' (1952) general equation for conductive heat transfer of freezing and thawing ground.

$$Z = \alpha\sqrt{t} \tag{4}$$

where: Z -denotes depth of the thaw plane (cm)
t -time elapsed from commencement of thawing (days)
α -constant, based on the thermal conductivity of the soil ($\text{cm s}^{1/2}$)

The equation states that there is a linear relationship between the depth of thaw and the square root of time when a step change in temperature is applied to the surface of a frozen, homogenous, semi-infinite medium. This study, like most other field studies, however, lacks much of the basic information necessary for the more complicated formulas normally done under laboratory conditions (such as those invoving the thermal conductivity, voumetric heat of the frozen soil and ice content) for predicting thaw. McRoberts (1975), however, concluded that the calculated constant values in Equation 4 have good agreement with measured values thus the equation is a reasonable model for active layer thaw development in field situations.

The production of the thaw rate curves, where thaw progression is plotted against the square root of time, allows for the quantitative comparison of thaw rates among the disturbances and the years. A random subsample (n=168 sites) of the thaw depth data was utilized for these curves. Least squares regression analysis on the thaw curves allowed for comparisons between the lines (Haag, 1973; Haag and Bliss, 1974; Mackay; 1970). In this simple linear regression analysis, the parameters can be interpreted as the intercept and the slope of the regression line. The slope can be regarded as the expected rate of change (thaw depth) in response to a unit change in the explanatory variable (the square root of time). The thaw rate differences are then calculated by using the **X** constant from the regression equations and expressing the increase as a percentage.

CHAPTER 4: RESULTS

THAW DEPTH RESULTS - A GENERAL OVERVIEW

Mean minimum thaw depths represent the thickness of the active layer at the initiation of spring frost probe measurements (Table 4.1). The maximum thaw depth values may or may not reflect the absolute maximum thickness of the active layer. Although considerable slowing down of the thaw rate suggested that the active layer was near attaining maximum seasonal thickness by the last probe survey at the end of August, further active layer development was probable.

Based on mean daily positive air temperatures for the Fort Norman and Norman Wells climate stations, the end of the thaw season, during the observation period, generally fell within the first two weeks of October (Atmospheric Environment Services, 1986 to 1988).

Table 4.1 Mean minimum, maximum and delta thaw depths for the three levels of disturbance as determined by the frost probe method. Values (cm) are averaged out over the four transects. Note that all measurements of the active layer thickness are from the ground surface to the top of the seasonal permafrost table. Ground subsidence has not been accounted for.

THAW DEPTHS	CONTROL			RIGHTS-OF-WAY			TRENCH		
	1986	1987	1988	1986	1987	1988	1986	1987	1988
MINIMUM [1]	16.1	14.7	9.4	19.7	16.6	7.7	24.3	19.7	8.1
Stand. dev.	7.8	5.7	5.3	10.4	7.8	4.7	17.0	10.0	4.9
MAXIMUM [2]	40.4	51.2	58.9	50.2	66.3	88.6	71.3	104.6	128.9
Stand. dev.	10.8	12.2	14.3	11.6	16.1	40.8	12.8	19.0	24.6
DELTA	24.6	37.3	49.7	30.8	52.2	76.7	48.5	84.5	120.9
Stand. dev.	11.5	12.9	15.6	13.8	15.8	29.4	21.1	22.7	21.4

[1] Minimum thaw June 20, 1986; May 26, 1987; May 11, 1988

[2] Maximum thaw August 26, 1986; August 27, 1987; August 31, 1988

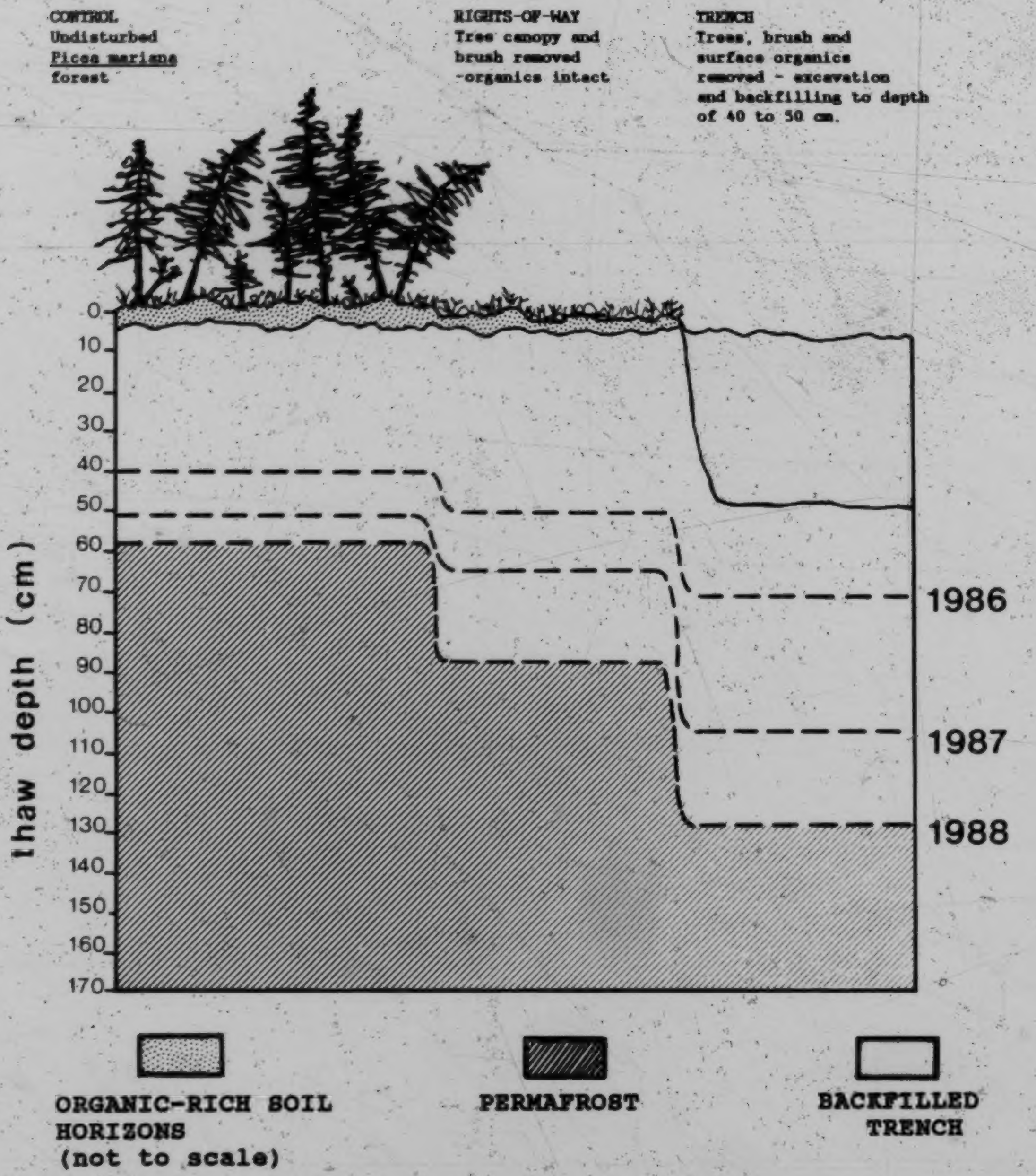

CONTROL
Undisturbed
Picea mariana
forest
RIGHTS-OF-WAY
Tree canopy and
brush removed
-organics intact
TRENCH
Trees, brush and
surface organics
removed - excavation
and backfilling to depth
of 40 to 50 cm.
Thaw depth (cm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
1986
1987
1988
ORGANIC-RICH SOIL
HORIZONS
(not to scale)
PERMAFROST
BACKFILLED
TRENCH

Figure 4.1 Generalized permafrost degradation under three different levels of disturbance over a three-year-period. Dashed lines represent the mean maximum thickness of the active layer at the end of each thaw season. Note - surface subsidence has not been considered in this diagram.

All levels of surface disturbance experienced permafrost degradation as indicated by the increase in the thickness of the active layer compared to the 1986 control with increases of 46%, 120%, and 220% for the 1988 control, ROW, and trench sites, respectively (Figure 4.1; Table 4.2).

Table 4.2 Increase in mean maximum thaw depths (cm) as determined by the frost probe method. Values are averaged over the four frost probe transects. Percent increase compared to the 1986 control thaw depths.

DISTURBANCE LEVEL	PERCENT INCREASE		
	1986	1987	1988
CONTROL	----	29	46
RIGHTS-OF-WAY	26	67	120
TRENCH	79	160	220

Each point on Figure 4.2 represents the mean maximum thaw depth for each probe site averaged out over the four transects. This figure demonstrates the position of the seasonal permafrost table at or near the end of the 1986, 1987, and 1988 thaw seasons. The general pattern of thaw remained relatively consistent from year to year while the magnitude of thaw increased. Considerable variation in thaw depth existed within each level of disturbance as well as between them. The very generalized position of the frost table as depicted in Figure 4.1 contradicts the complexity of the seasonal permafrost table (Figure 4.2). The complexity has been obscured by the use of mean values even with the generally homogeneous surface conditions that exist at the SEEDS site.

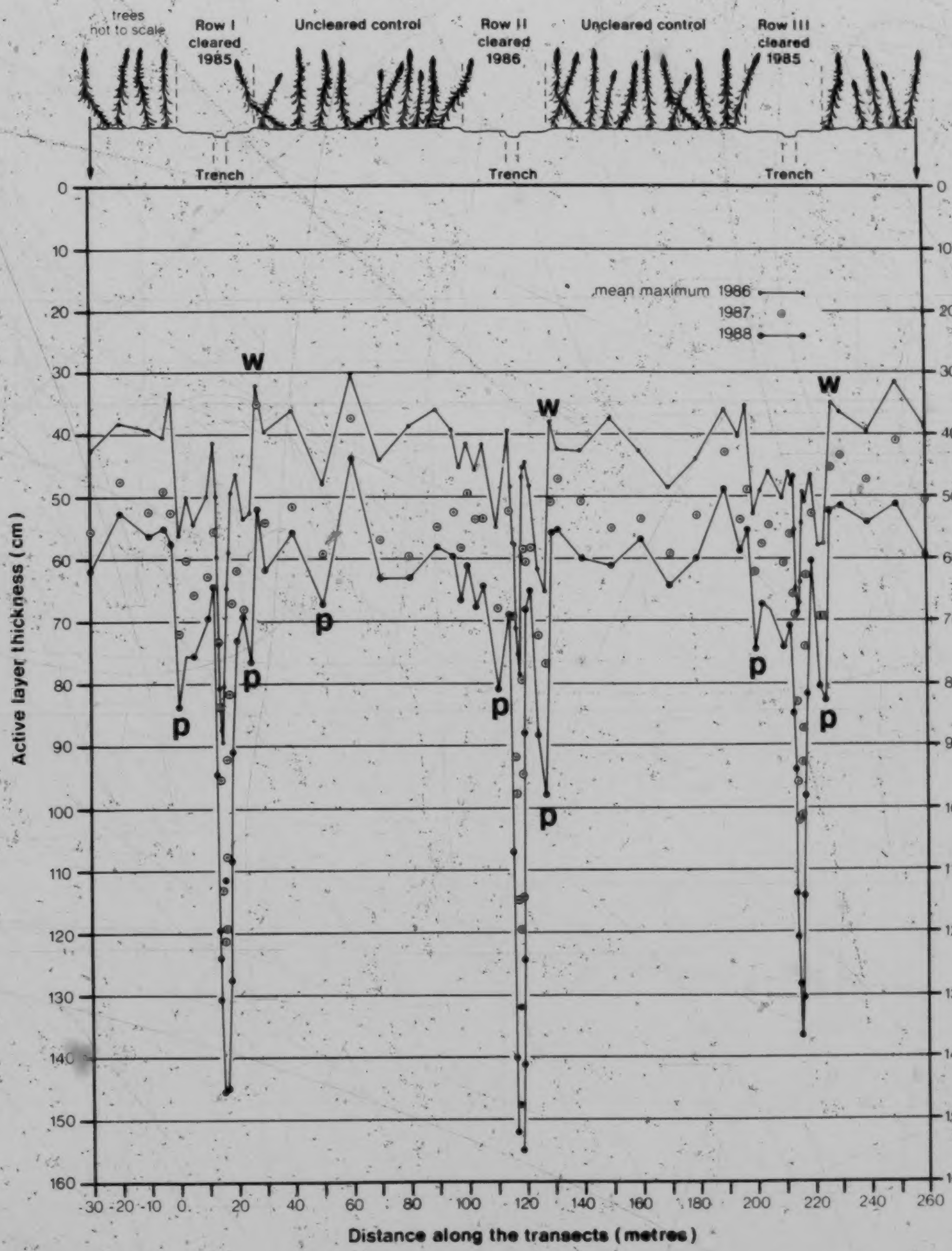


Figure 4.2 Cross section of study area showing the mean maximum thaw depths averaged over the four frost probe transects for 1986, 1987 and 1988. Note: trees are not drawn to scale. Footpaths - **p** , Windrows - **W**

OBJECTIVE 1 - SPATIAL VARIATION IN THAW DEPTHS AND RATES

H01 (A) No significant difference exists in the active layer thickness among the undisturbed control areas, the rights-of-way, and the simulated pipeline trench as a result of human-induced disturbances.

Significant mean maximum thaw depth differences ($P<0.00001$) existed between the control, rights-of-way, and the trench thaw depths in all three years of the study (Table 4.3).

Table 4.3 Summary of ANOVA results for mean maximum thaw depths among the three disturbance levels (control, ROW and trench). All comparisons based on $\log_{10}$ transformed data.

BETWEEN DISTURBANCES	D.F.	F RATIO	SIGNIFICANCE
1986	2	137, 57	***
1987	2	195, 78	***
1988	2	159. 80	***

D.F.: degrees of freedom

n sizes:	control	ROW	trench
1986	134	147	57
1987	135	142	60
1988	109	135	56

*** Probability of theoretical F exceeding calculated $F<0.00001$

While the ANOVA tests indicated significant overall differences in thaw depths for each year, F tests were used to compare the individual disturbances against each other (Table 4.4). In 1986 and 1988 there were significant differences ($p<0.05$ and $p<0.01$) between control-ROW, control-trench, and ROW-trench. In 1987, however, differences between the control and the ROW were not significant while the differences between the control-trench and ROW-trench were (p<0.05).

TABLE 4.4. Results of F tests of maximum thaw depth between disturbance evels. All values have been $\log_{10}$ transformed.

DISTURBANCE LEVELS	D.F.	F VALUE	SIGNIF.
1986			
CONTROL VS TRENCH	134, 57	2.21	**
CONTROL VS ROW	147, 134	1.28	**
ROW VS TRENCH	147, 57	1.73	**
1987			
CONTROL VS TRENCH	135, 60	1.46	*
CONTROL VS ROW	142, 60	1.07	
ROW VS TRENCH	142, 60	1.56	*
1988			
CONTROL VS TRENCH	125, 61	1.05	**
CONTROL VS ROW	150, 125	2.37	**
ROW VS TRENCH	150, 61	2.25	**

D.F.: degrees of freedom
Probability of theoretical F value exceeding calculated F: * P<0.05, ** P<0.01

HO1 (B) No significant differences occur in the rates of thaw between the control, rights-of-way, and the trench sites in the three years of the study.

The significant differences in the maximum thaw depths between the three levels of disturbance implies substantial differences in the rates of thaw (Table 4.5).

Table 4.5 Delta annual thaw depth values (cm), mean active layer thaw rates (cm/day) and standard deviations for the three levels of disturbance from 1986 to 1988.

	1986		1987		1988	
SITE	**DELTA**	**RATE**	**DELTA**	**RATE**	**DELTA**	**RATE**
CONTROL	24.6	0.38	37.3	0.40	49.7	0.44
Stand. dev.	11.5	0.19	12.9	0.14	15.6	0.14
RIGHTS-OF-WAY	30.8	0.58	52.2	0.67	76.7	0.69
Stand. dev.	13.8	0.27	15.8	0.17	29.4	0.26
TRENCH	48.5	0.80	84.5	0.19	120.9	1.06
Stand. dev	21.1	0.33	22.7	0.23	21.4	0.24

The major limitation to this method is that it assumes a constant rate of thaw throughout the summer thus obscuring any pattern or change in the rate. The thaw rate did not vary substantially both over individual thaw seasons and between years (Figure 4.3 and 4.5). Furthermore, there was a progressive decrease of thaw over the thaw season.

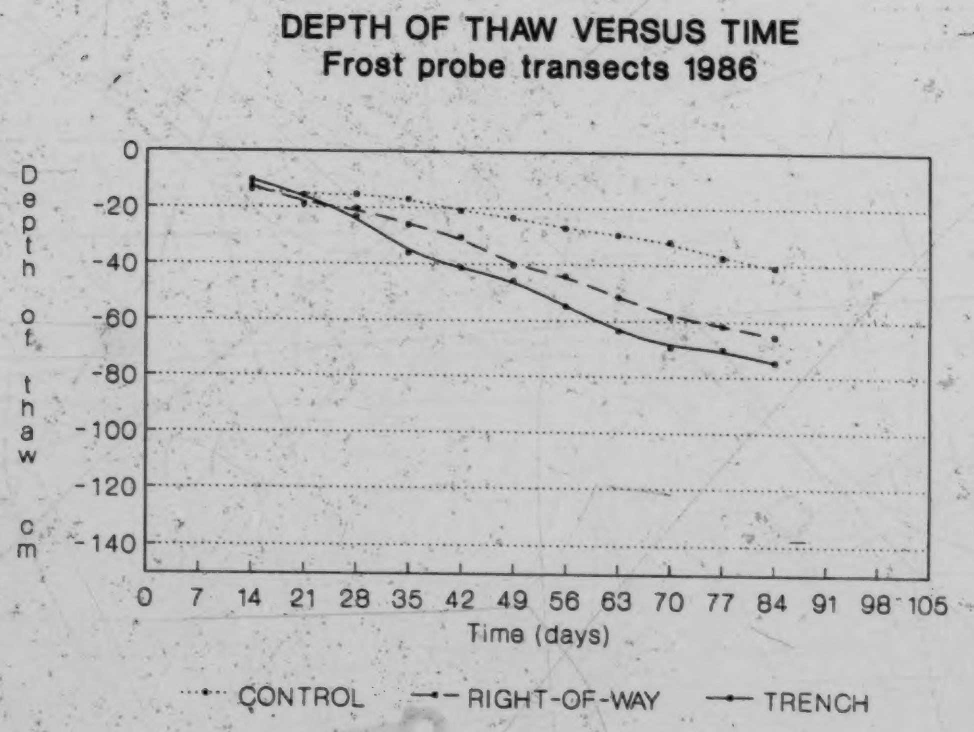


Figure 4.3 Second thaw season (1986) thaw depths for control, ROW, and trench sites versus time. (Day 0 = May 11)

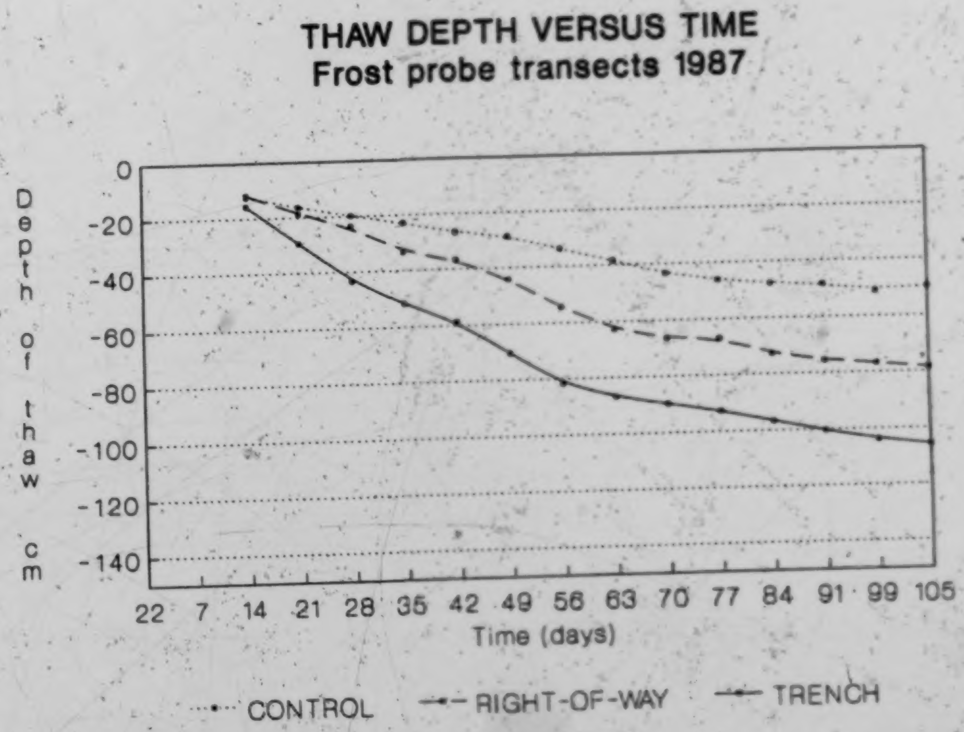


Figure 4.4 Third thaw season (1987) thaw depths for control, ROW, and trench sites versus time. (Day 0 = May 11)

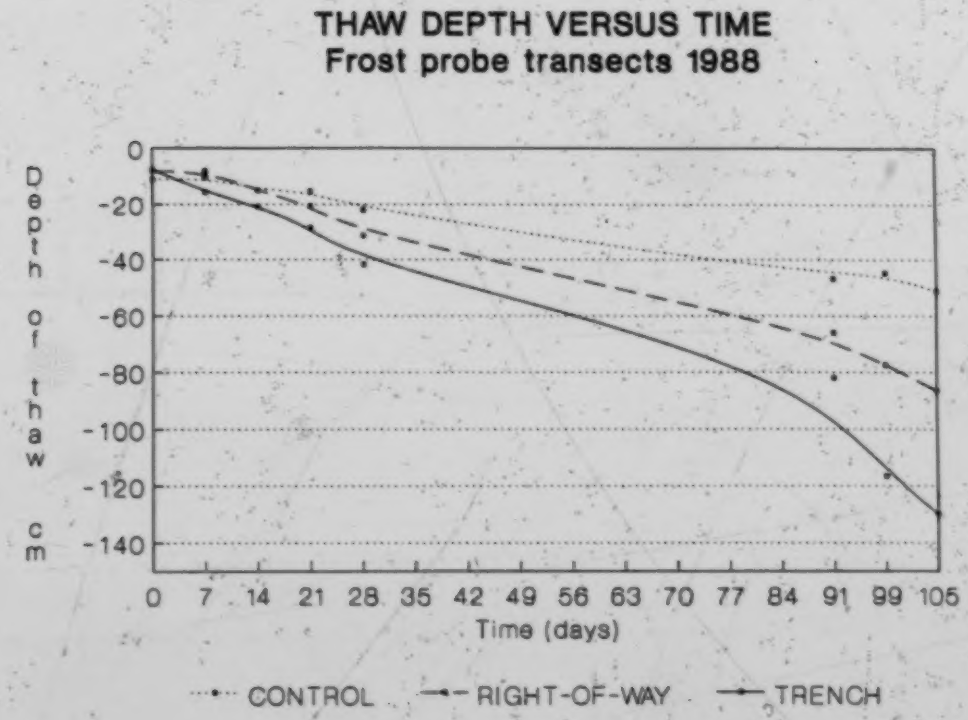


Figure 4.5 Fourth thaw season (1988) thaw depths for control, ROW, and trench sites versus time. (Day 0 = May 11)

In each year the slopes of the control curves were the lowest indicating the slowest rate of increase in the thaw depth, while the higher slope angles on the trench curves indicate much faster thaw rates (Figures 4.3 to 4.5). An increasing separation of the thaw rate curves for the three levels of disturbance is apparent over the duration of this study.

Following initiation of melt the trench soils thawed at a much more rapid rate than did either the control or the rights-of-way soils in all three years of the study. Quantitative comparison between the thaw curves was possible with the plotting of thaw progression against the square root of time (Figures 4.6 to 4.8).

Thaw rate differences (Table 4.6), calculated by means of least squares regression analysis indicated that the most significant difference was between the undisturbed control and the highly disturbed trench sites with 152% in 1986 and 115% in 1987. The gap in the June and July data for the 1988 thaw season makes percentage calculations based on the regression lines very tenuous. The rapid acceleration of thaw rates in August required the creation of separate regression lines for the beginning and end of the thaw season rather than just one line for each disturbance level.

R_2 values for the thaw depth versus the square root of time regression lines were very high for the 1986 and 1987 thaw seasons, ranging from $R_2 = 0.93$ to 0.99. Two regression lines for each level of disturbance were required for the 1988 thaw season due to the data collection gap for the months of June and July. Variation in the R_2 values for the 1988 thaw season thaw progression lines was considerable ranging between $R_2 = 0.45$ and $R_2 = 1.0$.

Table 4.6 Percent increase in thaw rates between control, ROW, and trench. Percentages based on the regression constants from the thaw slopes in Figures 4.6 to 4.8).

THAW SEASON	DISTURBANCES	THAW RATE INCREASES (%)	
1986		JUNE TO SEPTEMBER	
	CONTROL - ROW	105.58%	
	CONTROL - TRENCH	152.28%	
	ROW - TRENCH	22.72	
1987		MAY TO SEPTEMBER	
	CONTROL - ROW	72.90%	
	CONTROL - TRENCH	114.82	
	ROW - TRENCH	24.25%	
1988		MAY TO JUNE 7	AUGUST
	CONTROL - ROW	120.16%	356.76%
	CONTROL - TRENCH	205.28%	976.53%
	ROW - TRENCH	39.12%	135.69%

NOTE: 1988 percentage calculations were based on two regression lines per disturbance rather than one due to a divided sampling period.

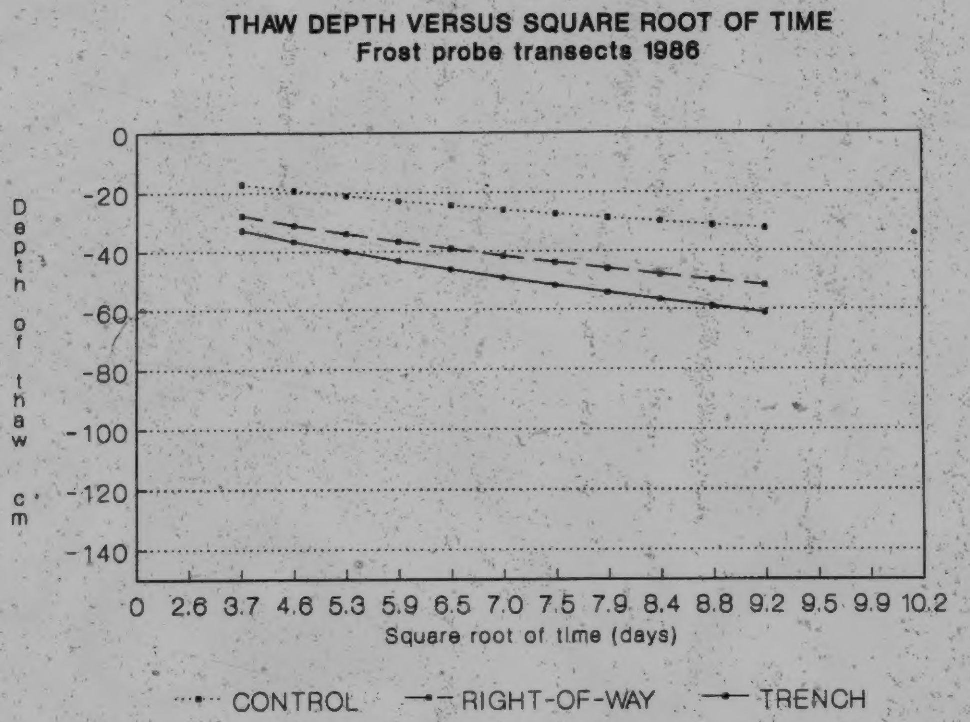


Figure 4.6 1986 thaw depth (Z) progression plotted against the square root of time. Note thaw Day 0 = May 11 or Julian Day 252).

CONTROL $Z = -21.4 + 5.91t^{-1/2}$ $R_2 = 0.93$
ROW $Z = -55.9 + 12.15t^{-1/2}$ $R_2 = 0.98$
TRENCH $Z = -70.6 + 14.91t^{-1/2}$ $R_2 = 0.99$

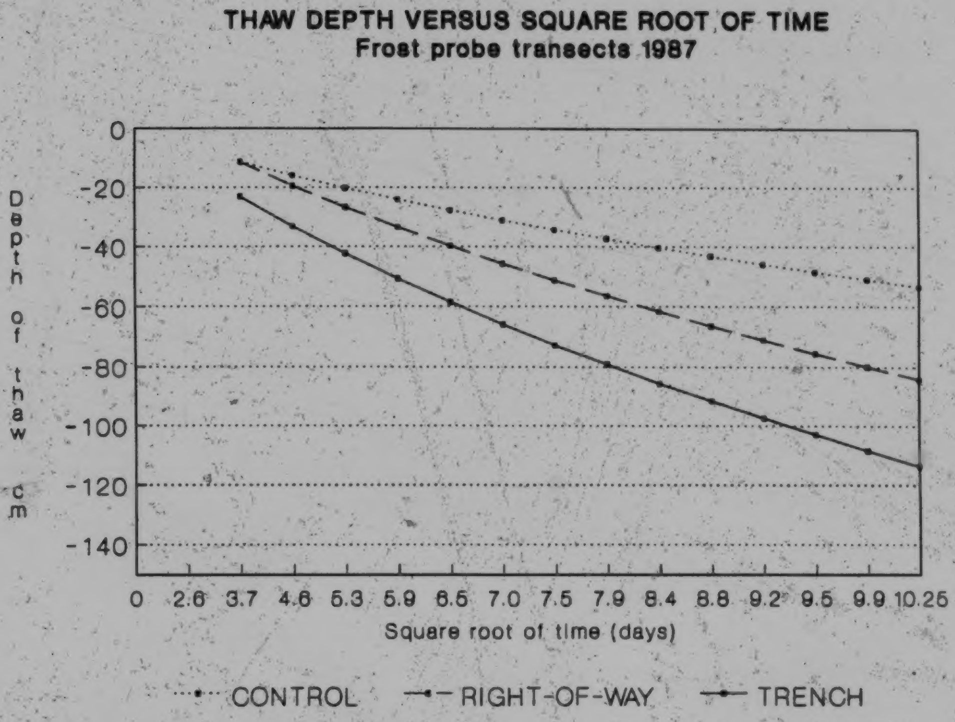


Figure 4.7 1987 thaw depth (Z) progression plotted against the square root of time. Note that Day 0 = May 11 or Julian day 252.

CONTROL $Z = -28.3 + 7.49t^{-1/2}$ $R_2 = 0.98$
ROW $Z = -57.2 + 12.95t^{-1/2}$ $R_2 = 0.98$
TRENCH $Z = -61.9 + 16.09t^{-1/2}$ $R_2 = 0.97$

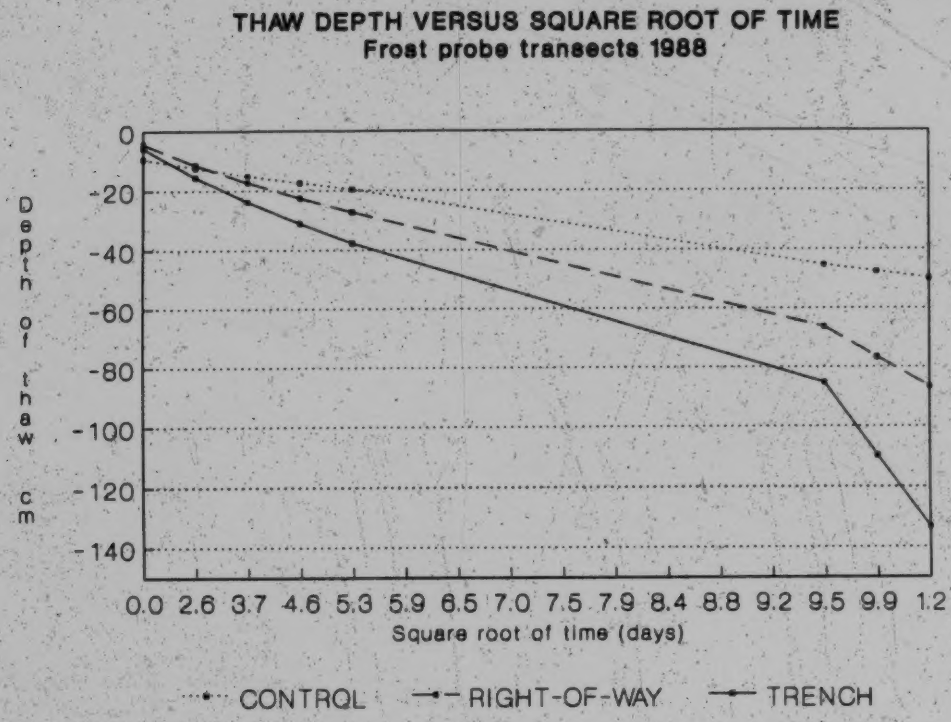


Figure 4.8 1988 thaw depth (Z) progression plotted against the the square root of time. Note that Day 0 = May 11 or Julian day 252. Note: that two regression lines were required for the 1988 data (May-June period and the August period).

CONTROL $Z = -5.16 + 3.82t^{-1/2}$ $R_2 = 0.79$
$Z = -23.73 + 6.73t^{-1/2}$ $R_2 = 0.45$

ROW $Z = -27.17 + 8.41t^{-1/2}$ $R_2 = 0.87$
$Z = -248.71 + 30.74t^{-1/2}$ $R_2 = 1.00$

TRENCH $Z = -38.11 + 11.70t^{-1/2}$ $R_2 = 0.95$
$Z = -657.11 + 72.45t^{-1/2}$ $R_2 = 0.94$

OBJECTIVE 2 - TEMPORAL VARIATION OF THAW DEPTHS AND RATES

H02(A) - no significant difference exists in the active layer thickness over the three seasons of thaw.

Seasonal progression of thaw

In 1986, 1987, and 1988 an average of 23% of the maximum recorded thaw depth for all levels of disturbance was attained by 30 May (Table 4.7). The percentage of maximum thaw attained at the end of each month for the control, ROW, and trench sites were similar in 1986 and 1988. The 1987 data were significantly higher in the percentage of thaw occurring early in the thaw season. An average of 64% of the maximum thaw occurred by the end of June in all disturbances. This was almost double the average June value for the other two years of the study. This accelerated rate reflects the fact that 90% of the maximum thaw was attained by the end of July in 1987, whereas in 1986 and 1988 only 65 to 75% of the total thaw was reached by that date.

Overall the percentage of thaw that occurred by the end of each month within the control, rights-of-way, and trench sites was remarkably similar although there were major differences in the thaw depths of the three areas. This implies significant differences in the thaw rates.

Table 4.7 Percent of maximum thaw attained by the end of each month (assumption that the end of August = 100% of maximum recorded thaw).

SITE	YEAR	MAY	JUNE	JULY	AUGUST
CONTROL	1986	---	37	65	100
	1987	29	61	88	100
	1988	25	39	---	100
ROW	1986	---	34	66	100
	1987	23	[illegible]	91	100
	1988	19	33	---	100
TRENCH	1986	---	29	75	100
	1987	19	67	89	100
	1988	21	39	---	100

--- MISSING DATA

The thaw depths of the three levels of disturbance were compared among the three years. In referring to each disturbance separately (Table 4.8), the differences between the mean maximum thaw depth within each of the disturbance levels were significant (P<0.00001) in all three years.

Table 4.8 Summary of ANOVA results for mean maximum thaw depths between the various years of observation (1986, 1987, 1988), by disturbance level. All comparisons based on $\log_{10}$ transformed data.

BETWEEN YEAR VARIATION	D.F.	F RATIO	SIGNIFICANCE
CONTROL	2, 391	89, 107	***
RIGHTS-OF-WAY	2, 436	126, 445	***
TRENCH	2, 175	120, 154	***

D.F.: degrees of freedom
n sizes:

	1986	1987	1988
control	134	135	125
rights-of-way	147	143	149
trench	57	60	61

*** Probability of theoretical F value exceeding calculated F<0.0001

When the disturbance levels were analyzed separately by means of T tests (Table 4.9), the mean maximum thaw depths were significantly different ($P<0.01$) from year to year for all levels. For example, the control 1986 thaw depths were significantly less than the control 1987 depths, and likewise for the 1987 and 1988 thaw depths. Significant differences existed between the ROW 1986, 1987, and 1988 thaw depths as well as the trench depths in each of the three years.

Table 4.9. Summary of difference of means tests (t tests) for mean maximum thaw depths between the years 1986 - 1987, and 1987 - 1988. Based on $\log_{10}$ transformed data.

YEARS	DISTURBANCE	D.F.	t VALUE	SIGNIF.
1986 - 1987	CONTROL	133, 134	8.74	**
	ROW	141, 146	10.08	**
	TRENCH	56, 59	10.79	**
1987 - 1988	CONTROL	124, 134	4.40	**
	ROW	141, 149	6.75	**
	TRENCH	59, 60	5.82	**

D.F.: degrees of freedom

** Probability of theoretical t value exceeding calculated $t<0.01$.

HO2 (B) No significant differences exist in the thaw rates on similar disturbances throughout the study site.

To test the proposition that the thaw rates were significantly different within the various levels of disturbance across the site, a one-way analysis of variance was undertaken on the data collected from each of the three years. The overall F ratios (Table 4.10) indicated significant differences among control, ROW, and trench thaw rates in all three years.

Table 4.10 Summary of ANOVA results for the mean thaw rates between the three levels of disturbance. All comparisons are based on $\log_{10}$ transformed data.

BETWEEN DISTURBANCES	D.F.	F RATIO	SIGNIF.
1986	2, 335	22.90	***
1987	2, 333	115.02	***
1988	2, 332	178.68	***

D.F.: degrees of freedom
*** Probability that the theoretical F value exceeds the calculated F <0.00001

n sizes:	1986	1987	1988
control	135	134	125
ROW	147	142	149
trench	56	60	61

Control thaw progression

In the control, thaw began in mid- to late May and progresses linearly until late August (Figure 4.9 (A)). Control soil temperatures apparently remained relatively constant during the first few weeks of thaw when the thaw depth increased to approximately 10 cm. As the layer of surface organics thaws the soil temperatures rise rapidly and the thaw of the underlying mineral soil proceeds at an accelerated rate.

There was little variation in thaw depth from year to year and the differences at any time during the thaw season were less than 20 cm. In all three years of observation there was a slight increase in the thaw depth between July and August suggesting that the thaw season was near completion. Maximum thaw for the three years was between 40 and 55 cm.

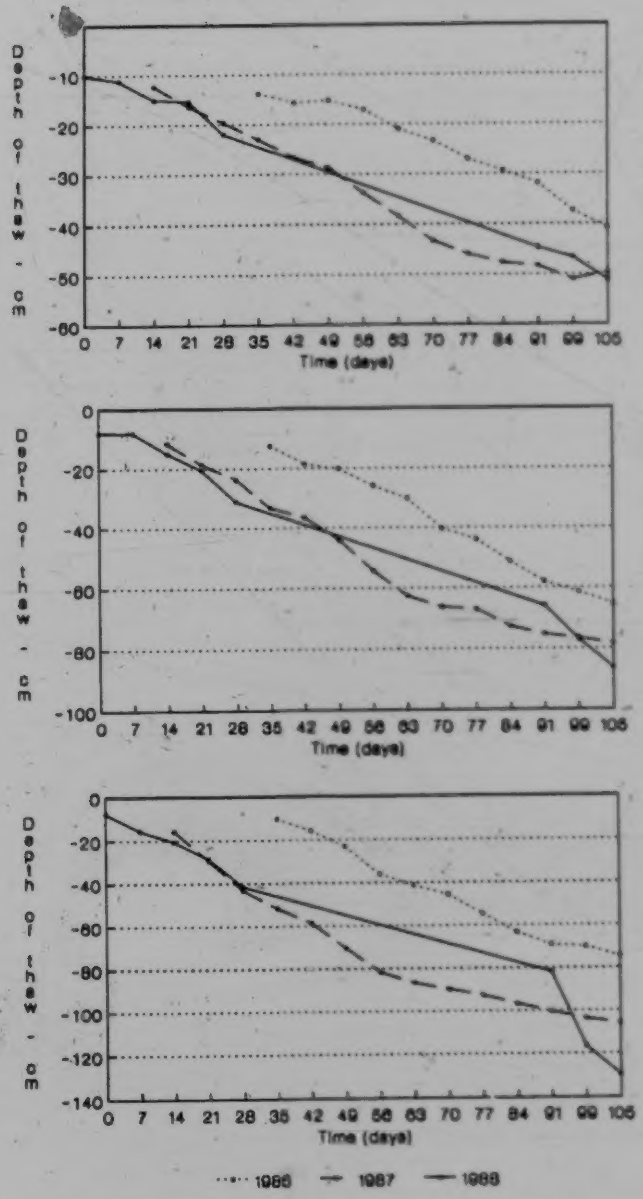
ROW thaw progression

In the hand-cleared rights-of-way areas the thaw depth pattern for the 2nd through the 4th season (1986 to 1988) followed closely to that of the undisturbed control with the thaw depths being deeper (Figure 4.9 (B)). The maximum thaw in late August is 10, 15 and 30 cm deeper than the control in the 2nd, 3rd, and 4th seasons, respectively. Instead of the simple linear thaw pattern as in the control, the ROW thaw rate curves indicate that most of the thaw occurred from mid-

June to mid- to late July. While the 2nd and 3rd seasons had relatively little (10 to 15 cm) increase in thaw depth in July and August, during the 4th season there was a much greater increase (30 cm) near the end of the thaw season.

Trench thaw progression

The seasonal thaw depth pattern in the trench was nearly linear in 1986, whereas in 1987 there was a period of rapid thaw in June which gradually levelled off by late July (Figure 4.9 (C)). In 1988 the pattern was more-or-less linear throughout the thaw season with a period of dramatic thawing during mid- to late August, similar to that which occurred in the ROW.



(A) control

(B) ROW

(C) trench

Figure 4.9 Thaw depth progression for the 1986 to 1988 thaw seasons. (A) control, (B) ROW, and (C) trench sites. Note that Day 0 = May 11.

OBJECTIVE 3 - EFFECT OF THE AGE OF THE DISTURBANCE ON THAW

HO3 (A) No significant differences exist in the active layer thickness associated with disturbances of different ages.

The effect of the age of the disturbance was considered by examining differences in thaw depth and rate between ROW 1 and 3, which were cleared and trenched in June 1985, with ROW 2 which was established in May/June 1986. Thaw depth measurements recorded in 1986 were therefore monitoring the second thaw season for ROW 1 and 3 and the first thaw season for ROW 2.

In 1986 the thaw depths (1986 -1987) on the ROW's were significantly different ($p<0.01$) while the trench sites were not (Table 4.11). The similarity in trench active layer thickness was unexpected. The fact that the trench in ROW 2 had experienced one less thaw season since intial disturbance had no effect on the thickness of the active layer. In order for the ROW 2 trench to obtain thaw depths similar to that of trench 1 and 3, the initial thaw following disturbance had to be quite rapid. The lack of significant differences in thaw rate between the different aged trenches implies that the thickness of the active layer in the previous thaw season had no bearing on the rate of thaw.

The significant difference in ROW thaw depth between the different aged disturbances may be a result of increased disturbances on the older ROWs due to more trampling associated with the conduction of other studies.

Table 4.11 F test results for maximum thaw depths of different aged disturbances. Comparison of one and two year old disturbances (1985 - 1986), and two-and three-year-old disturbances (1985 -1987). Based on $\log_{10}$ transformed values.

AGE OF DISTURBANCE	D.F.	F VALUE	SIGNIF.
1 VERSUS 2 YEARS OLD			
1985 - 1986 ROW	105, 46	1.79	**
1985 - 1986 TRENCHES	23, 38	1.28	n.s.
2 VERSUS 3 YEARS OLD			
1985 - 1987 ROW	101, 41	1.36	n.s.
1985 - 1987 TRENCHES	21, 39	2.50	**

D.F.: degrees of freedom
n.s.: F value not significant at the 0.05 probability
** :Probability of theoretical F exceeding calculated F<0.01

By August 1987, the age of the disturbance seemed to have no significant effect on ROW thaw depths. On the other hand, the thickness of the active layer under the 3- and 2-year-old trenched areas was significantly different (p<0.01). However, it was the younger disturbance (ROW 2) with the greater thaw depths not the older ones (ROW 1 and 3) as would be expected. There were no significant differences in the ROW or trench thaw rates between the different aged disturbances in either 1986 or 1987.

HO3 (B) No significant differences exist in the active layer thaw rates associated with surface disturbances of different ages.

In order to test the importance of the age of the disturbance on rights-of-way and trench thaw rates F tests were employed. As indicated in Table 4.12 no significant differences exist between the thaw rates of different aged ROW or trench disturbances.

Table 4.12 F tests results for the thaw rates of different aged disturbances. Comparison of one- and two-year-old disturbances (1985 - 1986) and two- and three-year-old disturbances (1987-1985). All comparisons based on $\log_{10}$ transformed data.

AGE OF DISTURBANCE	**D.F.**	**F VALUE**	**SIGNIF.**
1 VERSUS 2 YEARS OLD			
1985 - 1986 ROW	103, 43	1.13	n.s.
1985 - 1986 TRENCHES	36, 22	1.11	n.s.
2 VERSUS 3 YEARS OLD			
1985 - 1987 ROW	103, 43	1.11	n.s.
1985 - 1987 TRENCHES	41, 23	1.36	n.s.

D.F.: degrees of freedom
n.s.: F value not significant at the 0.05 probability

OBJECTIVE 4 - EFFECT OF VARIOUS TRENCH TREATMENTS

The various 'treatments' conducted on the simulated pipeline trench will have no effect on the thaw depth.

Insulation treatments

The frost probe lines cross both insulated and non-insulated portions of the trenches so that the effect of presence of insulation could be tested. The maximum thaw of the uninsulated portions of the trench encountered along the frost probe transects was somewhat deeper than the insulated portions during the 1986, 1987 and 1988 thaw seasons: 10%, 21% and 14% greater in these years, respectively (Table 4.13). Further statistical analysis was prevented by the limited number of samples from each treatment type.

Table 4.13 Mean maximum thaw depths (cm) for the trench and for the insulated and noninsulated trench treatments for the 1986, 1987, and 1988 thaw seasons.

THAW SEASON	ENTIRE TRENCH	INSULATED	NON INSULATED
1986	71	61	65
1987	104	85	103
1988	128	127	145

noninsulated n size - 20
insulated n size - 20

Revegetation treatments

In the first two years following the initial disturbance, mineral substrate and scattered clumps of organic material dominated much of the trench surface along ROWs 1 and 2. Mosses and several vascular plant species, including *Equisetum arvense* and *Epilobium angustifolium* have invaded the trench surface. In addition, some resprouting from intact organic material has provided plant cover, particularly along ROW 3. Insufficient growth of the agronomic grasses seeded in association with the revegetation trials had occurred by the end of the 1987 observation period to test the impact of vegetation cover on the thaw depths.

Effect of unintentional disturbances throughout the site

Apart from the major experimental disturbances created on the site, a number of minor unintentional disturbances resulted either from the monitoring programme or as a direct consequence of the initial study site design. These included generalized surface compaction (Plate 4.1), the access footpaths which ran along side of the ROWs and within the controls, and the windrows, composed of accumulations of trees and brush cleared from the rights-of-way, piled up along the eastern margins of the ROWs, 5 m within the control.

Footpaths generated relatively deep thaw depths on the margins of the rights-of-way (Figure 4.2). Although the organic mat was not intentionally removed, trampling compressed and eventually killed much of the vegetation along these trails. Compaction of the surface organics and the near-surface sediments resulted in linear depressions with depth of the depression being dependant upon the frequency of path use. Foot traffic was common along the footpaths throughout the thaw season as researchers gained access to various experiment locations. The most heavily used trails were depressed 20 to 30 cm in 1987. For much of the 1986 and 1987 thaw seasons major portions of these footpaths were filled with either standing or flowing water (Plate 4.2). Terrain disturbance along these footpaths resulted in the deepest active layer thickness (70 - 100 cm) on the site, only exceeded by the trenched areas.

The impacts of the windrows were most evident on the west sides of ROW 1 and 2 (Figure 4.2). Thaw depths beneath these slash accumulations were on average 5 to 10 cm shallower than the adjacent control thaw depths.

Plate 4.1 Example of localized ponding of surface water as a result of compaction of the surface organics and near-surface sediments. South link between ROW 1 and ROW 2, June 1987.

Plate 4.2 Dramatic example of localized surface depression as a result of foot and ATV traffic. Trail is occupied by flowing water throughout and long after the snowmelt season.

FROST TUBE RESULTS

A number of the tubes were cracked by the first inspection and the subsequent leaking of the fluoroscein dye deactivated them. Several had frozen into the outer PVC tubes thus preventing removal. Because of these problems freezeback was recorded only at a limited number of sites. In November the frost tubes located under ROW conditions revealed that, although freezing had taken place from the surface downward and the permafrost table upward, there was still a considerable zone of unfrozen material sandwiched between the converging freezing fronts. Kershaw (1988) noted that the temperatures at the 2 m depth did not stop rising until approximately 80 days after air temperatures had become predominantly sub-zero. This unfrozen zone or talik persisted in some of the ROW tubes until at least February. The control sites, on the other hand, were totally frozen during the first two winter excursions.

The following field season (June 1987), the cracked and damaged tubes were replaced and monitoring resumed following a thermal stabilization period of several weeks. Based on these observations active layer depths were greatest on the ROW sites and least within the control sites, thus supporting the frost probe information. By July most of the tubes, with the exception of three situated in the control, were completely thawed. By the end of August 1987, the freezeback process, from the permafrost table upwards had already begun.

SOIL MOISTURE CONTENT

Analyses of soil moisture contents were only conducted on samples from the control and ROW. The ROW samples were collected one year after clearing and therefore insufficient time may have passed to produce significant changes in the soil moisture profiles. Saturated conditions prohibited sampling of the trenched areas.

Near surface moisture conditions (0 - 45 cm)

The undisturbed sites had much higher mean near-surface soil moisture contents ($\bar{x}$=350%, S.D.=145) than the ROW sites ($\bar{x}$=170%, S.D.109) (Figures 4.10 and 4.11). The Of horizon thickness ranged between 3 and 18 cm ($\bar{x}$=8.5, S.D.=2.9) and the Om horizon ranged between 6 and 30 cm ($\bar{x}$=13.2, S.D.=5.3). The organic matter contents for the Om horizon varied between 16 and 77% with a mean of 45% (S.D.=15%). Because of this much caution must be used when interpreting these very large values. It would have been more meaningful to present this information in the form of percentage by frozen volume, however samples were collected with the permafrost corer, thus volumetric measurements were not taken in this context. The high variability in near-surface moisture content may reflect the varying thickness of surface organics throughout the site.

The near-surface (0-45 cm) moisture contents of the ROW sites were substantially lower than those of the control, with the means ranging between 160% at the surface to 90% at depth, compared with 350% to 85% in the control. The new homogeneity of surface conditions was reflected in the lower standard deviations for the ROW compared with the control.

Deeper moisture contents (45 - 225 cm)

Below the Of and Om horizons, in both the ROW and control soils (approximately 30 cm) there was a dramatic decrease in soil moisture content reaching a minimum of 80 - 90% at 45 cm (Figures 4.10 and 4.11). Of the top 75 cm of the soil profile it was the only zone in which the moisture contents of the two disturbances were not significantly different ($P<0.05$).

The control maximum was between 60 and 90 cm depth ranging from 110-120%. Upon passing through the ice-rich zone the moisture content progressively decreased with depth to approximately 30% at 225 cm. Below 100 cm there was very little difference between the ROW and control values or the amount of variability.

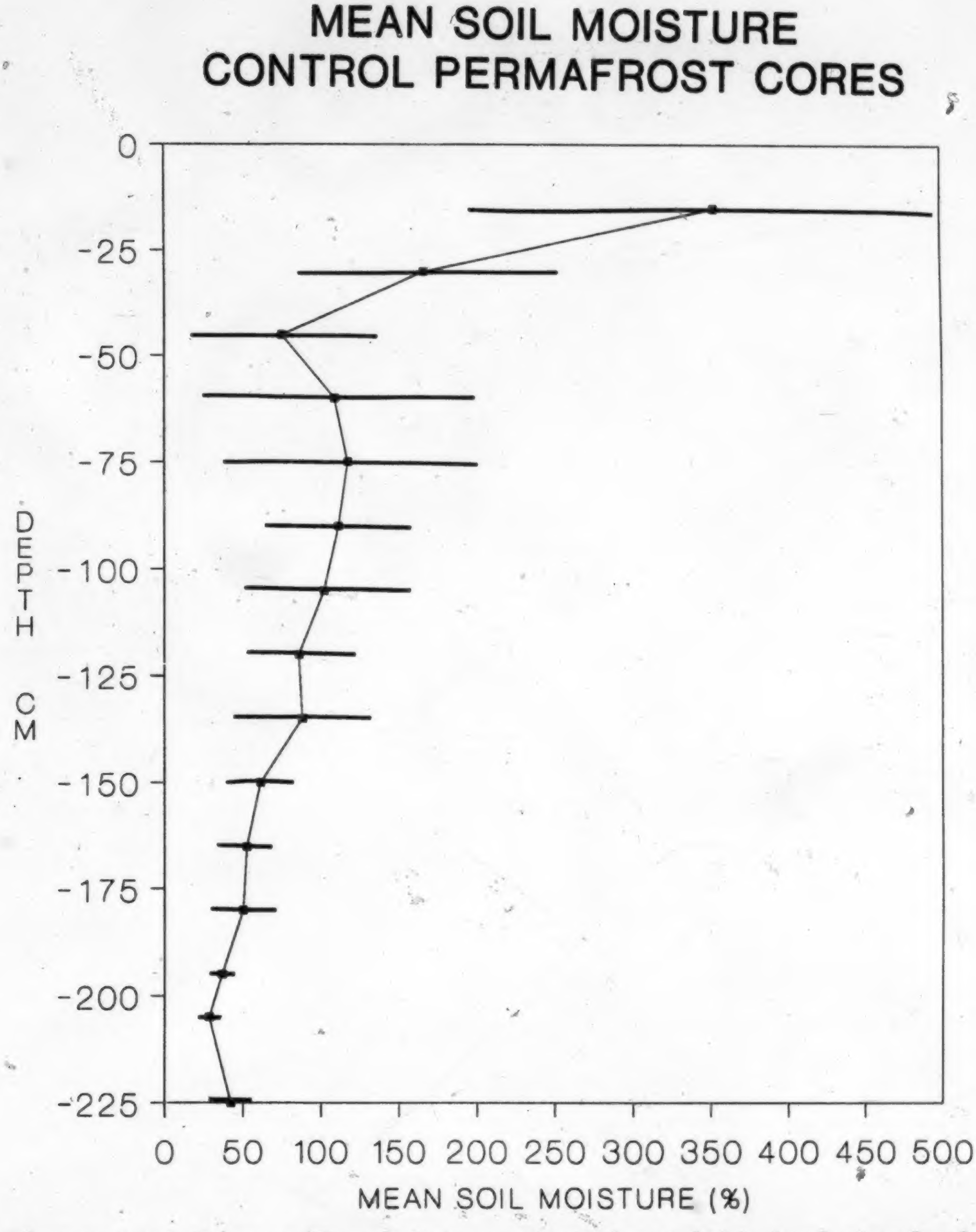


Figure 4.10 Mean soil moisture content by weight (and standard deviations) from undisturbed control permafrost cores. All samples collected in May and early June 1986.

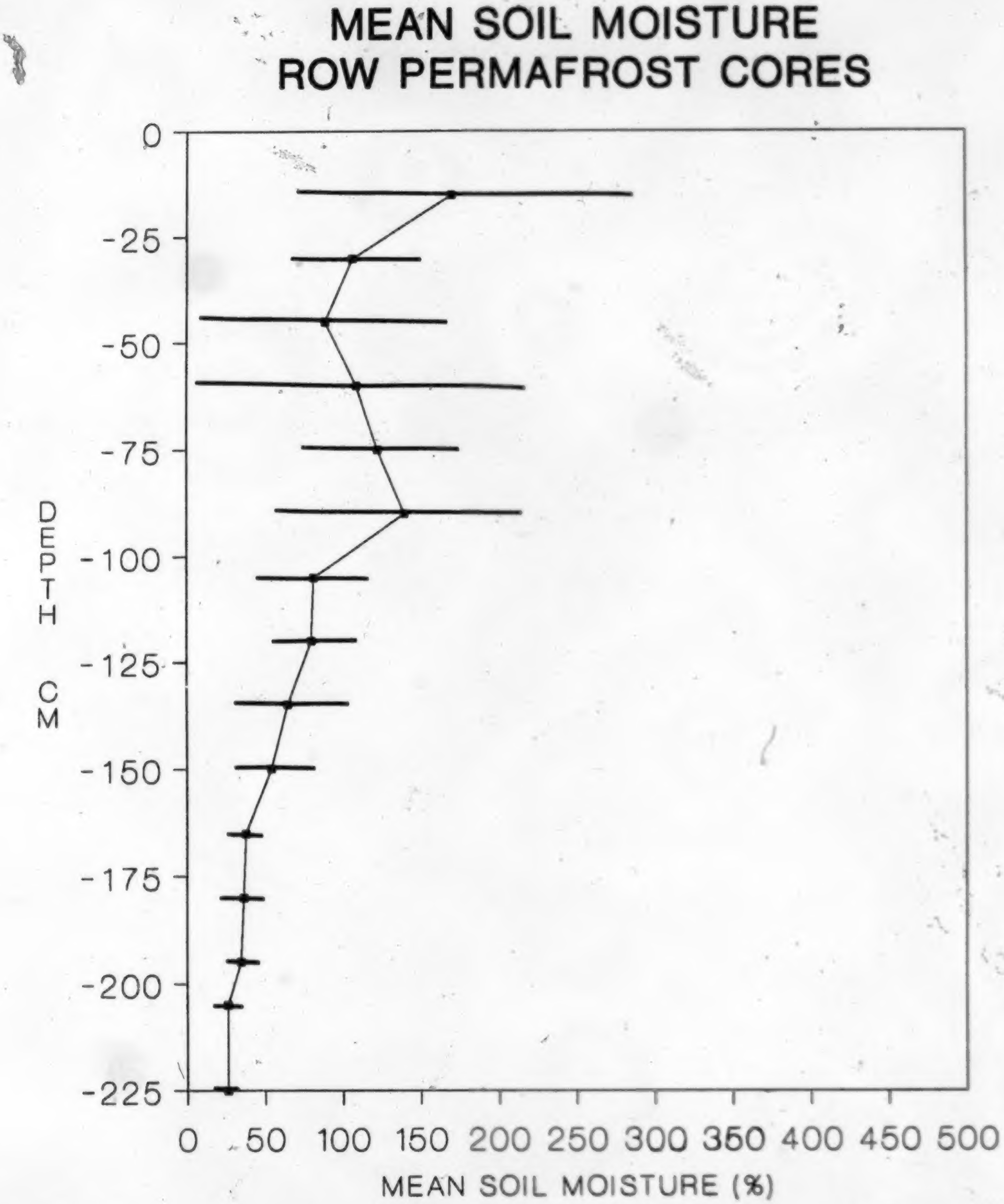


Figure 4.11 Mean soil moisture content by weight (and standard deviations) for cleared rights-of-way permafrost cores. All samples collected in May and early June of 1986.

Based on visual inspection of the 225 cm permafrost cores, the site was characterized by the ubiquitous presence of visible fine-grained crystals or minute grains in the soil interstices collectively classified as ice coatings (Vc) and pore ice (Vx). In virtually all core sample locations the pore ice was accompanied by segregated ice characterized by larger clusters of well-defined crystals (1 - 4 cm thick) (Vr and Vs). Several large transparent ice lenses (5 - 10 cm thick) were found during soil pit and other site excavations. Orientation of growth of these ice lenses was indicated by the long axes of these lenses being paralell to the freezing plane while the 'c' axes and bubble trains within the lenses were vertical. Fine horizontal clay and silt layers were visible within the lenses.

Maximum concentrations of ground ice were found at the 60 - 100 cm depth range generally as horizontal layers ranging in thickness from minute threads to several cm resulting from aggradational ice formation at the bottom of the active layer and upper layers of permafrost. The ground ice was spatially variable, both horizontally and vertically with cores only a few metres apart having distinct cryotextures and ice distributions. A few relatively ice-free cores were encountered and in most cases were associated with friable and compact clayey-silts.

Although ice content could not be determined from samples obtained by the coring procedures the percentage of ice by volume was determined through frozen bulk density samples (from 25 - 50 cm depths). On average, the ice content of the Cgy horizons was 57.3% by volume (S.D.=9.27, n= 20)

SOIL TEXTURE

The overall textural analysis for the SEEDS site soils showed that the percentage of clay-sized particles (<0.002 mm) remained relatively constant at 20.1% (Table 4.14). The fine sand fraction (>0.05 mm) varied the most between samples, ranging between 4% and 55%, averaging 25.3%. The remaining 54.65% was composed of silt-sized particles.

Table 4.14 Soil textural analysis - percent of total sample weight passing through the 0.05 mm and the <0.002 mm porportion determined by hydrometer analysis.

MEAN GRAIN SIZE	<0.05mm (SEIVE)	<0.002mm (HYDROMETER)
PERCENT	74.73	20.09
STANDARD DEVIATION	11.67	4.39
N SIZE	140	140

DISCUSSION

Williams (1982, 1989) concludes that the stable existence of permafrost is associated with the quasi-equilibrium of ground surface conditions and climate, while the processes of aggradation and/or degradation are associated with a positive or negative change in the ground energy balance. Within the discontinuous permafrost zone the ground temperatures hover near the freezing point thus leading to the natural instability of the position of the permafrost table when subjected to changes in vegetation and terrain conditions. This project focused on permafrost degradation resulting from a positive change in the ground energy balance associated with human-induced disturbances.

An original part of this study was to evaluate the changes which occur in the thermal regime of active layer and near-surface permafrost following various levels of human-induced disturbance. It was hoped that an understanding of the thermal regime could have been aquired through an analysis of the microclimate data collected at the site. The subsequent unavailability of the microclimate data severely limited the interpretation of the thaw depth and thaw rate information.

THAW DEPTHS AND THAW RATES

CONTROL AREAS

The ground surface in the undisturbed control was not subjected to intentional perturbation such as that in the cleared ROW or the excavated and backfilled simulated pipeline trench. Therefore, while the substantial increase in ROW and trench thaw depths were expected the relatively large increase in the control thaw depths over the three-year-period was not. Maximum thaw increased from 40.3 to 58.9 cm, or 46%. Despite the slight increase in the control active layer thickness over the duration of the study, the control sites had significantly shallower (P<0.0001) thaw depths than the ROW and trench sites in all years of the study. The majority of the total thaw occurred during the first 2 or 3 thaw seasons with the additional amount of thaw experienced by the control being significant. Following the initial impact of minor disturbance to the control sites the annual increase in the third year, although statistically significant, suggested that the magnitude of thaw increase was slowing down.

The control thaw depths exhibit slightly larger coefficient of variation values (CV=0.23) thus reflecting the irregular topography of the seasonal frost table. This complexity may be a result of greater variation in surface conditions such as vegetation cover, thickness of organic soil horizons, shading, drainage and microtopography. The undisturbed control section between ROW 1 and 3 (Figure 4.2) had considerable variation in thaw depth over short distances. Relatively shallow thaw depths within the control sites correspond to areas of greater tree density while the thicker active layer occurs in areas of surface disturbances such as footpaths.

Vegetation effects:

The undisturbed control soils experience the least amount of thaw because the presence of vegetation tends to promote and maintain low ground temperatures and a thinner active layer (Brown, 1963). In general the incoming summer solar radiation is reduced by canopy interception, evapotranspiration, and insulation by the organic layer. In the winter the combined effects of the presence of saturated surface organics and canopy interception of snow allow for deeper frost penetration.

Tree canopy shading is a major factor in maintaining the permafrost condition in this area of relatively warm permafrost. The net effect of tree cover is to substantially reduce the amount of heat reaching and entering the ground surface in the summer. Despite its openess, Lafleur and Adams (1986) concluded that the subarctic woodland canopy exerts a strong influence on the radiation regime at the ground surface. Although the black spruce canopy of the SEEDS site is sparse, it significantly reduced the radiation received and absorbed beneath it. Kershaw (1988) found that although the net radiation values for both the control and the ROW sites at a height of 4 m were similar, the net radiation in the control at the 1 m height was on average 20% less. Viereck (1965) and Gill (1974) have demonstrated how even individual trees can sufficiently influence the heat exchange at the ground surface to permit the existence of permafrost.

At Norman Wells, N.W.T. (80 km north of the SEEDS site) Haag (1973) and Haag and Bliss (1974a) found that approximately 60% of the total radiation was reflected, absorbed or dissipated before reaching the ground surface in undisturbed black spruce forest (48% canopy cover at 2 m) conditions. While 70% of the total incoming radiation penetrates through the canopy approximately 50% is absorbed by the vegetation, used for evapotranspiration and or is lost as sensible heat. Only 39% of the total incoming radiation penetrates to the ground surface of which only 17% is available for soil heat flux. The lower density of the tree canopy at the the SEEDS site (7% versus 48% at the Norman Wells site) would result in greater radiation penetration to the ground surface. The role of the tree canopy as a buffer between the atmosphere and the ground surface is thus reduced in the SEEDS site.

Organic soil horizon effects:

Along with the interception effects of the forest canopy, and perhaps more importantly, the living and dead organic layers at the ground surface provide an efficient layer of insulation promoting the existence of permafrost (Luthin and Guymon, 1974; Riseborough and Burn, 1988; Zoltai and Tarnocai, 1975). Riseborough (1985) suggested that the ground thermal regime within the boreal forest may be somewhat buffered from the effects of climatic change and canopy disturbance by the presence of these organic layers.

The moss and lichen layer at the surface and the high organic content in the Of and Om horizons have resulted in moisture contents averaging 350% primarily due to their high moisture retaining capacities and considerable quantities of excess ice. The interception and retention of precipitation and snow melt and the active withdrawl of soil water through evapotranspiration also help to explain these high values. The higher moisture contents may also be explained by the longer periods of snow cover (delayed melt and throughflow) and the cooler temperatures all as an effect of canopy shading. Moisture sampling was conducted in late May and June therefore the bulk of the moisture provided by snowmelt was likely still near the surface.

The major effect of these wet surface conditions is that a relatively large proportion of the net raditation is utilized in evapotranspiration thereby reducing energy that would otherwise be available for warming the ground. These processes serve to actively refrigerate the ground surface during the summer months (Williams, 1982). In the winter, following the autumn precipitation and thaw and refreezing of early snows the organic material becomes saturated thereby increasing the thermal conductivity and thus offering less resistance to the cooling of the underlying soil in winter than to the warming of it in summer (Nelson and Outcalt, 1982).

Snow conditions:

Snow depths at SEEDS were greatest under the forest canopy averaging 55 cm (range 49.6 to 60.8 cm) with a density of 177 Kg m^3 (Kershaw, 1990). Much snow reached the ground surface in the control because of limited interception by the narrow, cylindrical-canopied Picea mariana trees. Some insulation from winter air temperatures is provided by this low snow density and thus low thermally conductive snow cover. Although not of major significance at SEEDS, the spatial variations in the interception of snowfall by trees causes variations in snow depth associated with qamaniqs. Zoltai and Tarnocai (1975) and Desrocher and Granberg (1986) have shown how cavities in the snow cover that develop around spruce tree trunks and branches on the ground can cause appreciable cooling of the ground locally. The variability in snow depth within the forest, due to canopy variability, leads to microscale variation in the resistance to heat flow offered by the snow cover and therefore may have contributed to microscale differences observed in the thickness of the active layer.

The density and height of trees influence the ground surface wind velocities and consequently the latent heat loss. Wind speeds are lower in areas of dense trees than in areas where trees are sparse or absent. In the winter, surface roughness provided by the open-canopied forest reduces the effects of wind action thus preventing increased snow density resulting from wind redistribution. In areas of very sparse tree cover the increased thermal conductivity of the snowpack under these conditions allows for heat loss and cooler ground surface temperatures and shallower active layers (Goodwin, 1982; Nicholson and Granberg, 1973).

Regional climatic effects:

To the extent that the surficial environment within the control is undisturbed, a theoretical balance should exist between environmentally and climatically controlled geomorphic processes (Toy and Hadley, 1987). The relatively large increase of 46% in the mean maximum thaw depth between the 1986 and 1988 control sites was not expected since with the 'uniform' surface temperature under undisturbed conditions there should be an equilibrium of the thickness of the active layer.

The position of the permafrost table is an average condition. The surface temperature and length of the thaw season may oscillate around some long-term mean value (Lunardini, 1981). Short-term climatic anomolies such as an unusually cold winter, short summer, or thick snow cover can cause temporary changes in the average position of the permafrost table. Nicholson (1978a) suggests that the year-to-year variation of active layer thickness is mainly controlled by summer weather conditions. Several authors have reported that the normal variance of the mean active layer thickness may approach 25% from year to year (Brown, 1978; Nicholson, 1978). The increase in thaw depths may be attributable to the 1987 and 1988 thaw seasons which were longer than that of 1986 by 20 and 31 days, respectively. If it is not the actual length of the thaw season that is responsible for the increase in the active layer thickness then perhaps an increase in the total number of thaw degree days may account for it (Van Cleve and Viereck, 1981; Viereck, 1982). Based on yearly climate data (AES, 1986 - 1988) the cummulative thaw degree day totals for 1987 (1866 TDD) and 1988 (1834 TDD) for Norman Wells exceeds the 1986 total by only 110 and 78, which seems unlikely to have caused such an increase in the control active layer thickness. However, the

46% increase in the control thaw depth seems too high to be explained by normal annual variance alone.

An alternative explanation for the control thaw depth increase involves a change in the regional climate. Based on long-term trends in mean annual temperature records, Higuchi and Eitkin (1987) state that the temperatures in the Canadian Arctic as a whole have become more variable. The Mackenzie region, in particular, has displayed a clearly significant upward trend in the year-to-year change in annual temperature. Williams (1982) maintained that the magnitude of this annual fluctuation increased markedly since the early 1970's. At Norman Wells and Fort Simpson there is evidence of an increase in the mean annual temperature of approximately 2° to 2.5°C between 1986 and 1988. McInnes et al. (1989) suggest that this may reflect long-term climatic warming due to the effects of global environmental change or alternatively, the trend may represent a more localized and short-term climatic phenomena. Regardless of the duration of climatic change the increase in temperature must be considered and separated from the impact of human-induced disturbances in permafrost terrain.

Along the Norman Wells pipeline route 25% of the off-ROW (control) sites had evidence of warming although off-ROW mean surface temperatures were generally 1°C colder than the ROW temperatures and 2.5°C colder than the pipe or trench temperatures (McInnes et al., 1989). Surface temperatures from the thermal monitoring site closest to the SEEDS site (site 79.2 km) varied considerably from year-to-year. In 1986 the ROW mean annual temperature was -1.57°C and the control temperature was -1.92°C while in 1987 the ROW was -1.15°C and the control temperature -2.80°C. Although these values do not correspond directly to the results from the SEEDS site, this type of variability may likely have had an effect on the annual thaw depth.

Monitoring effects:

Dramatic changes in the control thaw depth between 1986 and 1987 may also be attributable to unintentional disturbance to the ground surface through the compaction of the organic and uppermost soil layers associated with the frost probing process itself as well as other activities that were carried out in the control areas. The net effect of such trampling is to increase the bulk density and thermal conductivity of the surface layers thus increasing the depth of the thaw (Isaacs and Code, 1972; Lawson, 1982, 1986).

Following the initial impact of minor disturbances to the control sites the annual increase in thaw depth decreased over time. The significant amount of thaw occurring during the first two thaw seasons may have resulted from the disturbance and subsequent melting of excess ice in the near-surface sediments (0 - 30 cm). Subsequent disturbance may not have been intense enough to maintain the response. Despite this increase in the control active layer thickness over the years, the control sites had significantly shallower thaw depths than the ROW and trench sites throughout the duration of the study.

The increase in thaw depth from 40.4 cm (1986) to 58.9 cm (1988) was not substantial enough to encounter the higher ice contents found at a depth of 60 - 90 cm (Figure 4.10). This maximum coincides with the aggradational ice layer at the base of the active layer and the top of the permafrost table (Burn and Smith, 1985; Mackay, 1971, 1977a, 1983).

Significant spatial deviations in thaw depth exist over distances as small as 0.5 m (Figure 4.2) possibly the result of spatial variation in microclimatic properties as influenced by vegetation, organic layer thickness, and drainage conditions. Variations of thaw depth within the control seem to be most closely related to the density of vegetation cover. Nicholson (1978b) found a very strong correlation between active layer thickness and percent vegetation cover in Schefferville, Quebec.

MODERATELY DISTURBED RIGHTS-OF-WAY AREAS

The rights-of-way, associated with hand-clearing of the forest canopy and the maintenence of the organic mat, represents the intermediate level of human disturbance. As a result the increase in the thickness of the ROW active layer was also intermediate between the undisturbed control and the highly disturbed trench areas. By August 1988 the mean maximum thaw depth had increased by 38.4 cm (77%) compared to the 1986 ROW and 48.2 cm (120%) over the original control thaw depths. A 32.1% increase occurred between 1986 and 1987, and 33.6% between 1987 and 1988. The additional amount of thaw occurring with each thaw season was virtually the same, suggesting little change in the condition of the ROW between the three years.

Vegetation effects:

The removal of the forest canopy which eliminates shading and insulation effects on the ground surface temperature regime has been well documented in the literature (Brown and Grave, 1979; Linell, 1973; Nicholson, 1978a, among others). The most probable cause of the increase in the mean maximum thaw depths on the ROWs is the increase of 20% in net radiation following canopy removal (Kershaw, 1988). Haags' study (1973) of seismic lines near Norman Wells, N.W.T. concluded that the removal of the vegetation canopy resulted in little change in albedo or net radiation but there was a major change with respect to the ground surface climate. Vegetation removal resulted in a large increase in the amount of energy that penetrated to the ground due to the removal of canopy shading. Soil heat flux accounted for 17% of the incoming radiation (30% of the total radiation) thus increasing the soil temperature throughout the year. Haag and Bliss (1974a) suggested that the removal of the forest canopy alone increased the soil temperatures and depth of thaw if only as the result of the change from a three-dimensional to a two-dimensional energy absorbing system.

Organic soil horizon effects:

Under ROW conditions there are no trees and tall shrubs to intercept the incoming radiation before it reaches the ground surface. Thermal resistance to the atmosphere is provided by the surface organics, both living and dead. The ground thermal regime within the boreal forest is buffered from the effects of climatic change and surface disturbance by the presence of these organic layers (Luthin and Guymon, 1974). The importance of the moss and lichen layer in protecting the permafrost from atmospheric heat is demonstrated by the fact that although there was some increase in the thaw depth following canopy removal the maintenance of the surface organics limited this increase. The ROW organics remained essentially intact although many of the mosses and lichens became desiccated. Increased radiation, temperature and wind speed all contribute to higher evapotranspiration rates. The lower near-surface soil moisture contents of the ROW sites (170% vs 350% in the control) demonstrates this drying out process. The lower moisture contents in the near-surface sediments may also reflect internal drainage associated with the increased thaw depths. The water released from the melting of excess ice may migrate down the soil profile or laterally to lower elevations.

The new homogeneity of surface conditions, created by the removal of the spatially irregular tree canopy, is also reflected by the lower standard deviations for the ROW moisture contents compared with the control. In some cases the effects of extreme desiccation and trampling lead to mortality of the surface plant cover (Kershaw, 1988). These dried organics with their low thermal conductivity, provided an effective vapour and temperature barrier. Additional insolation on the cleared ROWs is utilized in sensible heating rather than being used for evapotranspiration.

The increase in the ROW active layer thickness compared to the control is associated with the down profile migration (15 cm) of the zone of maximum moisture content. The moisture contents were also about 30% greater suggesting that more moisture (water released as ground ice melts) moved towards the new deeper freezing plane. Below 100 cm there was very little difference between the ROW and control values or in the amount of variability.

Heginbottom (1971, 1973), in his study of the effects of surface disturbance on ground ice content and distribution following the 1968 Inuvik N.W.T. fire demonstrated a similar downward shift in maximum excess ice content following disturbance. The ground disturbance lead to a virtual disappearance of excess ice in the top metre (from 60% to 20%) and a significant increase in the second metre (from 20% to 50%). Below 3 m there was little or no change in the ice content. Gersper and Challinor (1975) reported a similar downward migration of the moisture content on tundra tracks.

Snow conditions

The rights-of-way are characterized by a snowpack that is on average 10 cm thinner (mean snow depth of 44 cm) than that of the undisturbed control (Kershaw, 1991). The lack of canopy interception of snow which would result in thicker snow cover is offset by increased wind velocities. Redistribution of the ROW snow cover by wind reduced the thickness of the snowpack thereby increasing its density slightly and thus its thermal conductivity. According to Kershaw (1991) the ROW snowpack had higher heat transfer coefficient values than did the undisturbed forest snowpack and as a result should be losing more heat in the winter than in the adjacent forest sites. The net effect being to reduce soil temperatures through enhanced heat loss from the ROW sites. However this effect, if real, must be substantially reversed in the thaw season since significantly greater thaw depths occur on the ROW sites as compared to the control. The insulating quality of the ROW organic mat may efficiently buffer the underlying soil thus offsetting the heat transfer characteristics of the snowpack.

Monitoring effects:

Although the low shrub layer (<0.05 m) and the moss and lichen layer were left intact, some degree of compaction and disturbance to the ground surface was inevitable during the removal of the tree canopy. Numerous research projects also conducted on the rights-of-way have had unintentional impacts on the ROW ground surface. Compaction of the surface organics and upper layers of soil resulting from foot traffic may result in an increase in bulk density and subsequently the thermal conductivity.

Haag and Bliss (1974a, 1974b) and Gersper and Challinor (1975) noted that compaction of the organic layers on winter roads and tundra tracks have resulted in an increase in bulk density with depth leading to an increase in thermal conductivity and soil heat flux. Compaction on the SEEDS site resulted in different degrees of active layer thickening, varying with the intensity of compaction and its effects upon drainage.

Along some of the pathways and minor ephemeral drainage courses the organics and upper soil layers have become saturated as a result of compaction and lowering resulting in unintentional permafrost degradation. Haag and Bliss (1974a) and Haag (1973), on the otherhand, suggest that the thaw depth under such saturated depressions may be reduced because a majority of the atmospheric heat is used in the latent heat of evaporation rather than as soil heat flux because evapotranspiration accounts for 50% of the net radiation on seismic lines.

Several authors (Adam and Hernandez, 1977; Heginbottom, 1973; Kurfurst, 1973; Pihlainen, 1962) have reported that the removal of the forest canopy by hand without significant compaction of the surface organics will have negligible (increases of twice the original depth or less), and in some cases undetectable short-term impacts on the depth of thaw. These and other studies show the importance of latitudinal variation in annual temperature as being a controlling factor in active layer response to disturbance. The presence of low mean annual temperatures and less dense vegetation canopies at many of the sites, helped to reduce the impact of surface disturbance. Linell (1973) demonstrated that with respect to permafrost degradation in the Fairbanks region:

> "the preservation of low surface vegetation ..... cannot by itself be relied upon to prevent long-range degradation of the permafrost in a region of relatively warm permafrost temperatures like Fairbanks." (pg 692)

The thaw depths under the ROW conditions at the Fairbanks site increased by 300% after 26 years. The minimum 120% increase in mean thaw depth experienced on the SEEDS rights-of-ways after only 4 thaw seasons (1985 - 1988) is in agreement with Linells' conclusions.

INTENSELY DISTURBED TRENCHED AREAS

The trenched sites had the most significant change in thaw depth and thaw rate as a result of experiencing the greatest severity of disturbance. Mean maximum thaw in 1986 was 71.3 cm, 31.1 cm deeper than the control. By the end of the 1988 thaw season the mean maximum thaw depth beneath the trenched areas had increased by 57.6 cm (80%) over the 1986 trench thaw depth and increased 3.3 times over that of the original active layer thickness. The amount of additional thaw experienced with each successive thaw season decreased from 76% (control'86 - trench'86) to 58% (trench'86 -'87) and finally 42% (trench'87 - '88).

The trench had the lowest coefficient of variation values (CV = 0.18). This suggests that the production of relatively homogeneous surface conditions associated with the trenching process resulted in a less complex topography of the frost table than under the undisturbed conditions of the control or slightly disturbed ROW.

The stripping of the surface vegetation and excavation and backfilling of the trench caused a dramatic change in the surface energy balance compared to the undisturbed control or the ROW. Several factors combine to bring about the penetration of increased soil heat into the disturbed soils and the subsequently large thaw depths of the trenched areas. As with the apparent increase in soil temperatures associated with canopy removal experienced under ROW conditions, the trench sites additionally experienced changes associated with the loss of the organic layers, settling and compaction, changes in albedo and snow conditions, and fluvial-thermal processes.

Organic soil horizons:

The removal of the insulating surface organic layer was the most important effect of the simulated pipeline disturbance. The valuable buffering effects provided to the rights-of-way soils by the moss and lichen surface are absent in the trenched areas.

Kurfurst (1977) has shown that the removal of light coloured lichens and mosses that occurs with surface disturbance results in the exposure of the darker humus or mineral soil layer and significant reduction of surface albedo. In the summer the albedo of the bare soil sections is low with most of the heating of the ground surface resulting from solar input and direct contact with the warmer air temperatures. The net effect of the decreased surface albedo is warmer soil temperatures and deeper thawing. This effect was noted in fireline soils of Alaska (Viereck, 1982) where, compared to the control, the number of thaw days increased from 847 to 940. In addition, the trenching process itself was one of 'passive thawing' (Esch, 1984) which allowed heat penetration through both the surface of the trench and the lateral walls for the brief time period during excavation and before backfilling. Kershaw (1988) reported that during August, the -2 m soil temperatures in the trenched segments of ROW 1 were often more than 13°C greater than those of the adjacent rights-of-way.

Fluvial-thermal effects

Post-construction changes resulted in the settling and compaction of the backfilled trench sediments which lead to linear depressions characterized either by sections of ponded or occasionally flowing water. Because the trenches were lower than the surrounding area they attracted meltwater and precipitation runoff. The overall south-west to north-east slope of the SEEDS site resulted in the interception of numerous minor drainage channels that flow obliquely to the north-south oriented trenches. The volume of water flowing down the trenches was supplemented by these 'tributaries' (Figure 4.12).

In the spring the water arrived in the trenches at relatively high temperatures which promoted the ablation of the snow. The rapid removal of snow from the trench by meltwater action attenuates the spring cooling effect on the underlying soil. In many low-lying sections of the trench residual bodies of standing water remained frozen through the snowmelt period and persisted long after the melting of the rest of the trough. The high surface ice content of the

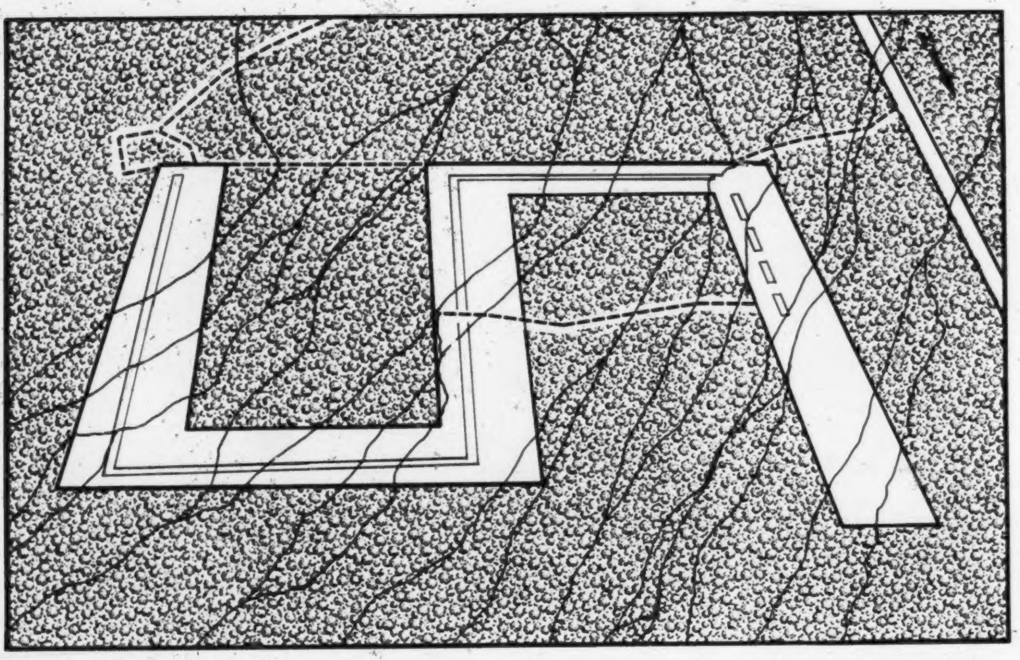


Figure 4.12 Location of intermittent and minor drainage channels and seepage zones throughout the SEEDS site as identified from areal photographs. View from the North, dashed lines are footpaths and ATC trails (1987).

trench soils may delay the onset of spring thaw by one or two weeks. Viereck (1982) noted a similar situation with Alaskan fireline soils.

Surface water is an important source of heat for permafrost degradation. During the summer in subarctic regions surface water is under the influence of extended sunshine hours and its associated heating. Water seeps into the soil or is moved along the surface in drainage paths at relatively high temperatures. Rapid thawing of the permafrost can result from either or both ways (Linell and Tedrow, 1981). Fluvio-thermal processes along the trench as well as ponding of water in the trench segments may contribute to warming of the soils and Nelson and Outcalt (1982) suggest that the heat stored in these water bodies may produce a positive feedback effect through which further thaw subsidence and ponding may occur. Similar findings were reported from the Norman Wells Pipeline right-of-way (Hardy, 1986; IPL, 1986; Wishart, 1988) where sections of subsided trench lines were filled with ponded and/or flowing water. Spring runoff draining into a non-operating gas pipeline ditch at the Norman Wells test site (Walker, 1972) contributed to double the amount of thaw in the ditch compared to the adjacent right-of-way.

The saturated condition of the trench soils may affect the soil temperatures year-round. Saturated soils are amenable to thermal conductivity because they conduct heat 10 times more readily than when dry. The warmer summer soil temperatures and greater moisture contents of Alaska firelines (Viereck, 1982) caused a delay in the fall freezeback of the surface by several weeks. In the winter standing water on the surface acted as a thermal sink while freezing, thereby decreasing the amount of soil cooling. Complete freezeback at the Alaskan sites was not attained until February. Burgess and Harry (1990) report that the thermal influence of the generally wet Norman Wells Pipeline trench soils may help to explain the warmer winter soil temperatures. Heat released during freezeback of the wet soils would delay, reduce or even prevent winter cooling. Time domain reflectivity (TDR) measurements confirm the unfrozen ground conditions in the vicinity of the IPL trench during the winter months.

Snow conditions

Winter snow is drifted into the depressed trenches by winds completely filling them in and producing planar topography. The effect of this deeper snow cover is to protect the trenches from the direct impact of the winter cold. Snow depths within the trench averaged 42 cm with a mean density of 187 kg m^3 (Kershaw, 1991). Warmer temperatures may result at the ground surface and play an important role in increasing the trench thaw (Nelson and Outcalt, 1982), on the otherhand, late-lying snowcover may actually retard the thawing of the soil during the early part of the thaw season. Where snow melt is rapid this cooling effect may be negligible.

Insulation and revegetation treatments

Various reclamation and protection treatments were conducted along alternate stretches of the simulated pipeline trench. Both the insulated and non-insulated treatments experienced relatively different thaw depths with slightly higher values being encountered in the non-insulated sections. The increase in thaw depth under uninsulated conditions was 10%, 21%, and 14% for the three thaw seasons between 1986 and 1988. The tree slash and brush that was backfilled into the trench provided some degree of insulation for the trench soils by limiting the downward penetration of heat. The degree of insulation, however, was not consistent over time.

No significant difference was noted in the thaw depths and temperatures (Kershaw, 1988) in the fertilized and seeded reclamation plots, perhaps conditions 3 to 4 years following the intial disturbance were not yet stabilized and were still responding to the original disturbance. The revegetation of the trench by the end of the 4th growing season appeared to have little influence on the thaw depths. Up to this point the influence of the disturbance itself far outweighed that of the re-establishment of a plant cover. The low ground cover along some portions of the trench may be attributed to a number of factors including the lack of time since seeding, the presence of standing or flowing water, and fluvial erosion and deposition of the trench substrate. The last two factors may have resulted in the drowning, redistribution, loss and or burial of the seeds or seedlings at the SEEDS site (Maslen, 1989).

It is expected that within a few years the ground cover and organic detrius should be considerable enough to have some effect in stabilizing the disturbed areas and in minimizing thaw depths by reducing the soil heat flux (Rouse, 1982). According to Viereck (1982) the development of this organic layer is the most important control of the active layer depth by vegetation. Along with the organic mat plant cover assists in stabilizing and eventually reducing the thickness of the active layer by increasing the albedo of the exposed mineral surface (Bliss and Wein, 1973, Hernandez, 1973, Johnson, 1978; Younkin, 1976) and by reducing the surface moisture content by transpiring water out of the soil (Wishart, 1988).

While Wishart (1988) concludes that the presence of roots are an important means of stabilizing the substrate and preventing erosion on slopes, Viereck (1982) claims that the reseeding has had little effect on slowing the depth of thaw on Alaskan firelines. Linell (1973) concluded that under similar climatic and environmental conditions as Fairbanks (same latitude as the SEEDS site), the reestablishment of a vegetation cover could not be counted on to stop or prevent permafrost degradation in a area subjected to surface disturbance. The reestablishment of a feathermoss surface, the most important component of the surface cover, may take as long as 50 to 75 years (Veireck, 1982).

Lateral degradation processes

The dramatic increase in thaw depth was not the only significant response following the excavation and backfilling of the trench. In the first thaw season following the creation of the trench frost probe measurements showed that there was an abrupt plunge of the frost table at the margin of the trench. Over time, however, the lateral slopes of the trench became unstable and gravitational processes (micro-slumping and spalling) expanded the degradation into the adjacent ROW. The lateral expansion along the trench depressions is reflected in a corresponding expansion of the thaw bulb beneath the trench (Figure 4.2).

THAW PROGRESSION AND THAW RATES

Thaw initiation is closely correlated with the completion of snowmelt. During snowmelt, thaw is minimal so long as the snow remains on the ground surface even though air temperature might be well above freezing. Late-lying snow persisted well into the spring with relatively rapid melting occurring during the month of May. The snowmelt season was relatively brief with the complete snowmelt runoff period lasting approximately two weeks. The shortness of this period is typical of the subarctic region (Kane and Stein, 1983; Slaughter and Benson, 1986).

The earliest disappearence of snow was from the rights-of-way, then the control, and finally from the trenched areas and the snow drifts along the edges of the ROWs. Once the snow is removed the thaw progresses rapidly as the ground surface temperatures approach those of the air temperatures.

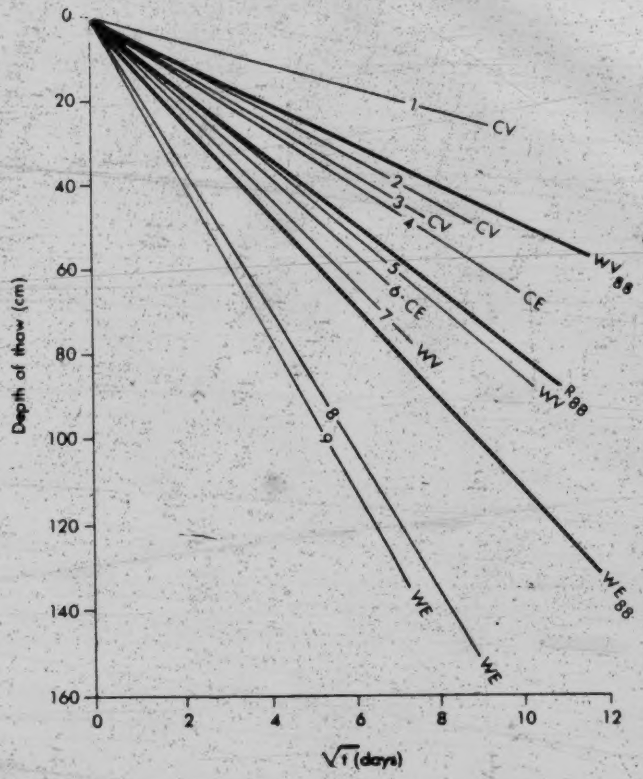
The most dramatic changes in the thermal energy balance occur as the result of the replacement of the high albedo of the snow by the relatively low albedo of the newly exposed soil and vegetation surfaces. As a result of this albedo change the radiation absorbed at the ground surface increases greatly, however, not all of this energy is available for warming the soil. Weller and Holmgren (in Williams, 1982) claim that only 9% of this energy is used to heat the soil while 73% is involved in the melting of the frozen soil water and to evaporate this water from the moss and lichen surface following the complete disappearence of the snow cover. The rapidity of thaw is primarily the result of heat conduction processes and the percolation of meltwater through the soil under gravity. The heat conduction process being a function of the accumulated degree day totals. The specific heat capacity of the thawed soil decreases with drainage thereby increasing the rate of thaw.

The thaw of the soil progresses rapidly at first but slows down over the season because of the increasing thickness of the upper layer of thawed soil. Viereck and Lev (1983) reported similar findings in Alaska with rapid intial thawing in the spring with 50% of total thaw occurring by the end of June, and 80% by the end of July. Jahn (1985) suggested that the upper thawed zone becomes an insulation layer and thus provides resistance to downward heat transfer thereby slowing any subsequent thaw. The overall decrease in the thawing process after the first half of the summer is the general rule (Jahn and Walker, 1983; Viereck, 1982). By the end of August the thickness of the active layer becomes relatively stabilized with the mean maximum thaw being attained between mid-August and mid-September. During the 1986 and 1987 field seasons there was little increase in thaw depth during the last half of August as the soil began to freeze upwards from the permafrost table. This upward movement of the 0°C isotherm was demonstrated by the advancing freezing fronts in the frost tubes.

Thaw depth versus time

The plots of thaw depth versus the square root of time permit the comparison of the thaw rates among the various levels of disturbance and between geographically different sites. McRoberts (1975) and Jahn and Walker (1983) summarized several case studies of thaw progression throughout the arctic and subarctic regions (Figure 4.13). In most cases there is a marked linear relationship between the depth of thawing and the the square root of time in accordance with Equation 4. Jahn and Walker (1983) concluded that the different lengths of lines and angle of inclination suggest that the "regular mechanism of thawing" is affected by different climate or vegetation conditions. The warm summer sites (warmest month >5°C) and those sites without insulative vegetation cover have the longest and steepest correlation lines reflecting the greatest thaw depths and the fastest thaw rates. Sites 8 and 9 on Figure 4.14 are typical of the SEEDS' trench sites with their increased soil heat flux and lower moisture content at depth. Lower evapotranspiration and thus latent heat requirements for thaw mean that any additional energy to the system (e.g. as a result of canopy and organic layer removal) could be utilized for sensible heating.

The shorter and gentler slopes of sites 5 and 7 would be typical of the conditions under the undisturbed subarctic boreal forest, with its shallower active layer and slower thaw rates. Thaw rate curves for the rights-of-way would be represented by the intermediate positions representing the intermediate level of surface disturbance. Haag and Bliss' (1974a) thaw curves from the Norman Wells region, although shallower, are in good agreement with those of this study. The Norman Wells control thaw depth progression line would be similar to CV #1 and the seismic thaw progression similar to CV #2 (Figure 4.14).



CV - cool summers/vegetated
1. Yenisei Estuary
2. Greenland
3. Franz Joseph Land

CE - cool summers /unvegetated
4. Yenisei Estuary
6. Spitsbergen

WV - warm summers /vegetated
5. Colville River delta
7. Barrow, Alaska

WE - warm summers /unvegetated
8. Colville River delta
9. Gulkana, Alaska

Figure 4.14 Soil thaw development in different arctic and subarctic regions (after Jahn and Walker, 1983). Cool summers are defined as the warmest month being <5°C, whereas the warm summers have the warmest month >5°C. **WV_{88}** - 1988 control thaw progression, and R^{88} - ROW SEEDS site and **WE_{88}** - 1988 trench thaw progression

SEASONAL THAW PROGRESSION - VARIATION BETWEEN YEARS

2nd season thaw progression (1986)

Thaw depths for all three disturbance levels at the beginning of the 1986 monitoring period were approximately 10 to 15 cm. The shallow thaw depths indicate that the thaw process had just begun. In the spring of 1986 cold air temperatures and the persistence of snow slowed the initiation of thaw until late into the season - June 20 (Figure 4.9). As the summer progressed the ROW and trench thaw depths, while paralleling one another, began to exceed that of the control by 10 to 20 cm. The thicker active layers in these areas could only be attained by increased thaw rates. Only 10 cm separated the ROW and trench at the end of the second thaw season.

3rd season thaw progression

Monitoring of the frost probe transects in 1987 began one month earlier than in 1986. Once again the thaw process had only just begun with thaw depths for the three levels of disturbance being approximately 10 to 15 cm. The earlier initiation of thaw reflected a warmer spring and earlier removal of the snow cover than in 1986. The rapid separation of the thaw depth curves indicates substantial changes in the thaw rates of the ROW and trench disturbances.

4th season thaw progression

In 1988 frost probe monitoring again began shortly after thaw initiation showing similar shallow thaw depths in the control, ROW and trenched areas. A major data gap exists between June 7 and August 1. Prior to this period the thaw pattern was relatively linear for the three areas. When thaw monitoring resumed in August there was a dramatic rejuvenation in the thaw rates and thaw depths for the ROW and trench sites (Figure 4.8). The most probable cause for this apparent rejuvenation is sampling error, in particular, a failure (by inexperienced field assistants) to determine the true thaw depth during the first August probe survey. Mackay (1977) and Nelson and Outcalt (1982) emphasize that the thaw depths should be related, in part, to the force applied by the observer and in this case the "force" was evidently not correctly applied.

SOIL MOISTURE CONTENT

Moisture content is dependent upon those factors responsible for soil formation including; climate, parent material, relief or topography, internal and external drainage, vegetation and time. Considerable microsite variation of some of these parameters within the study site has contributed to the highly variable soil moisture contents as is demonstrated in the high standard deviation values.

The moisture content (and implied ice content) within the active layer and near-surface permafrost was highly variable both areally and with depth. The permafrost cores revealed a wide range of moisture contents ranging from soils that were relatively dry with little or no ice content, to soils dominated by visible pore ice, to ice-rich cores with significant excess aggradational or segregated ice crystals and/or lenses. In many cases the ice lenses reached proportions of greater than 10 cm in length. According to Johnston (1981) the presence of soil particles within these lenses distinguishes them as being segregated ice rather than intrusive ice which would be composed of pure water.

The highest mean moisture content and variability is within the first 100 cm, thus reflecting the highly variable surface and substrate conditions, particularily in microclimate, vegetation, and drainage, that exists on a microscale. This near-surface zone is enriched with water from both the atmosphere (precipitation and snowmelt) and the thawing active layer. Water migrates downward toward the still frozen active layer and the upper layer of permafrost along temperature and hydraulic gradients (Burn and Smith, 1985). The fact that the moisture transfer does occur within the active layer and near-surface permafrost throughout the thawing and freezing periods means that the moisture and ice content values are constantly changing over one year. The values obtained during this study, therefore, are indicative of the early thaw season moisture contents only.

The variation in the quantity and distribution of soil moisture suggests relatively distinct surface and ground temperature regimes and responses to disturbance. The soils dominated by pore ice would yield relatively less excess water upon thawing compared to the ice-rich soils. Ice content values averaged 57.3% by volume, falling in the mid- to high-excess ice category as defined by Ytyurin (in Grave, 1983). Permafrost degradation associated with human disturbance would thus have a greater impact on ice-rich soils leading to thaw consolidation and subsidence.

SOIL TEXTURE

Soil texture has a regulatory influence on the growth and form of ice in the soil by influencing (1) the freezing temperature of the phase boundary water and the water in fine capillaries and (2) the movement of water to the freezing front (Washburn, 1979).

Several authors (Linell and Kaplar, 1966; Taber, 1930) conlude that suction potential (due to high pore pressures) and permeability is maximized in silt-sized soils allowing water to freely migrate to the freezing plane thus favouring ice lens and segregated ice development. This mechanism is partially responsible for the development of the ice-rich aggradational ice zone located at the base of the active layer (at depths of approximately 60-75 cm in control and 90 cm in the ROW sites). This zone of aggradational ice at the base of the seasonal active layer and the top of the permafrost table is, however, not restricted to silt-sized soils (Burn and Smith, 1985; Harris, 1986; Mackay, 1971, 1977a, 1983).

It is commonly understood that the amount of unfrozen water varies inversely with the grain size. In general, the amount of unfrozen water in a soil at a given temperature increases with decreasing grain size (Williams, 1982). The basic factor accounting for the different freezing temperatures is the greatly increased contact area between solids and water as grain size is reduced and the resulting tendency for surface effects to keep capillary and phase boundary water from crystallizing. Lau and Lawrence (1977) have reported that in the fine-grained glaciolacustrine soils of the Central Mackenzie Valley considerable proportions of the water exist in a liquid phase year round.

While the textural composition influences the growth and form of ground ice it also has a pronounced influence on the rate and depth of seasonal thaw and on permafrost degradation in the event of thermal disturbance. The discontinuous permafrost at this site is considered to be 'warm' with temperatures (0°C to - 2.5°C) such that a small heat input or extraction of heat could change the ice:water content of the soils (Judge, 1973; Riseborough and Burn, 1988). The large amount of unfrozen water in the regional soils as a result of their fine-grained texture would suggest that the amount of heat required to cause thawing would be reduced and thus the soils would be susceptible to minor disturbances.

FROST / THAW SUSCEPTIBILITY

These soils are classified as frost susceptible based on the widely accepted criteria first set out by Casagrande (1932) and later adopted by the US Corp of Engineers. On average, 75% of the soils sampled from the SEEDS site are smaller than 0.05 mm in diameter thus suggesting a high susceptibility to freezing and thawing processes.

Testing for liquid limits was conducted on Cgy horizon soils in association with bulk density and ice volume determinations. Liquid limits ranged from 27.5% to 55.5% with an average of 38.6% (n= 20, S.D.=8.74). The silt loams of the site were of a low plasticity with a mean plastic limit of 19.7% and the plasticity index of 18.9. Virtually all samples from these horizons had moisture contents that exceeded the liquid limits thus suggesting the possibility for slope failure, solifluction, and other mass movement or instability processes.

CONCLUSIONS

Over the last few decades there has been a growing awareness of the importance of anthropogenic geomorphology in the North and the significance of inadvertant effects on geomorphic processes. Of particular interest has been the changes in the ground temperature and the thickness of the active layer in response to human disturbances.

An attempt was made to follow the evolution of the degradational process rather than to take the 'post-mortem' approach (Kerfoot, 1973) of many of the recent studies. The major probem with these studies involves the assumption of identical terrain conditions between disturbances that may be several years or decades old and the present day adjacent undisturbed control areas. The post-mortem approach may also obscure any variation in the rates of degradation over time.

Controlled human-induced perturbations initiated on the SEEDS site have had an effect on the thickness and rates of thaw of the active layer. In general, all disturbances had an increased thaw depth relative to the undisturbed control. Removal of the black spruce canopy associated with the clearing of the rights-of-way resulted in a large increase in energy penetration to the ground surface resulting in an increased downward heat flux in the summer thus leading to a thickening of the active layer. Where the understory vegetation and the organic mat were left in place the active layer thickening averaged 120% during the three years of observation. Preservation of the organic mat has obviously reduced the magnitude and rate of permafrost degradation due to its high specific heat capacity and low thermal conductivity. The thickness of the active layer beneath the trenched areas increased by an average of 220% during the same time period. The 46% increase in thaw depths under control conditions was unexpected and may be related to a regional climatic warming trend and/or monitoring-induced surface disturbances.

The comparative thaw profiles in adjacent sites show that the degree of alteration in the vegetation canopy and in the organic mat determined the impact on the thermal regime and consequent degradation of the near-surface permafrost. The greater the degree of disruption the greater the depth of thaw. The pattern remained the same for the three thaw seasons of observation although the amount of degradation became more pronounced over time. The fact that the rights-of-way and trench disturbances were not initiated at the same time (ROW 1 and 3 in 1985, ROW 2 in 1986) had no significant effect on the depths and rates of thaw. The insulation treatments conducted on the simulated pipeline trench did result in slightly shallower thaw depths. As of August 1988 there had been insufficient revegetation of the trench surface to have an effect on the thaw depth that was distinct from that of the initial disturbance. The establishement of a vegetation cover on some portions of the trench, however, has aided in the stabilization of the surface and the reduction of surface run-off and erosion.

The frost tubes proved to be a simple and accurate (good correlation with frost probe data) method for determining the position of the freezing and/or thawing fronts. Unfortunately, the deactivation of a large number of the tubes by cracking and leaking and the long thermal re-stabilization period seriously limited the available data and the subsequent interpretation.

The position of the seasonal frost table cannot be considered as uniform even under generally homogenous surface conditions. Considerable variation of thaw depth exists within each level of disturbance as well as between them. The infinite variation of ground surface conditions (including snow cover, vegetation shading, relief, soil moisture, etc.) over very small distances undoubtedly contributes to the high variability in thaw depths and rates. These micro-scale differences may not be significant for engineering purposes but may have important ecological and environmental implications. This large, within-system variability contributes to the difficulty of making generalizations about the impacts of terrain disturbance.

The seemingly simple effects of the removal of the forest canopy and the organic mat associated with northern disturbances actually has a significant impact on the surface energy balance and thus the thaw depths involving alterations to the insolation, albedo, soil thermal conductivity, evapotranspiration rates, snow accumulation, and drainage patterns. It is apparent that the near-surface permafrost at the SEEDS site is at temperatures such that a small input of heat, such as that following vegetation or surface disturbance, would be sufficient to considerably change the ice to water ratio of the soils. In the ice-rich and thaw susceptible soils of the Mackenzie Valley, terrain disturbance could and has been significant. In addition to the direct effects of surface disturbance, the implications of climate change should be carefully considered as any additional heat input may result in increased permafrost degradation.

This study, in effect, is similar to Mackays' (1971) process response chart of permafrost degradation (Figure 4.3). The process in this case has been a vegetational disturbance with the result being increased ground surface temperature. The initial terrain response was the degradation of the near-surface permafrost. The physical consequences of active layer thickening include the formation of thermokarst topography and slope instability and will be examined in the following paper.

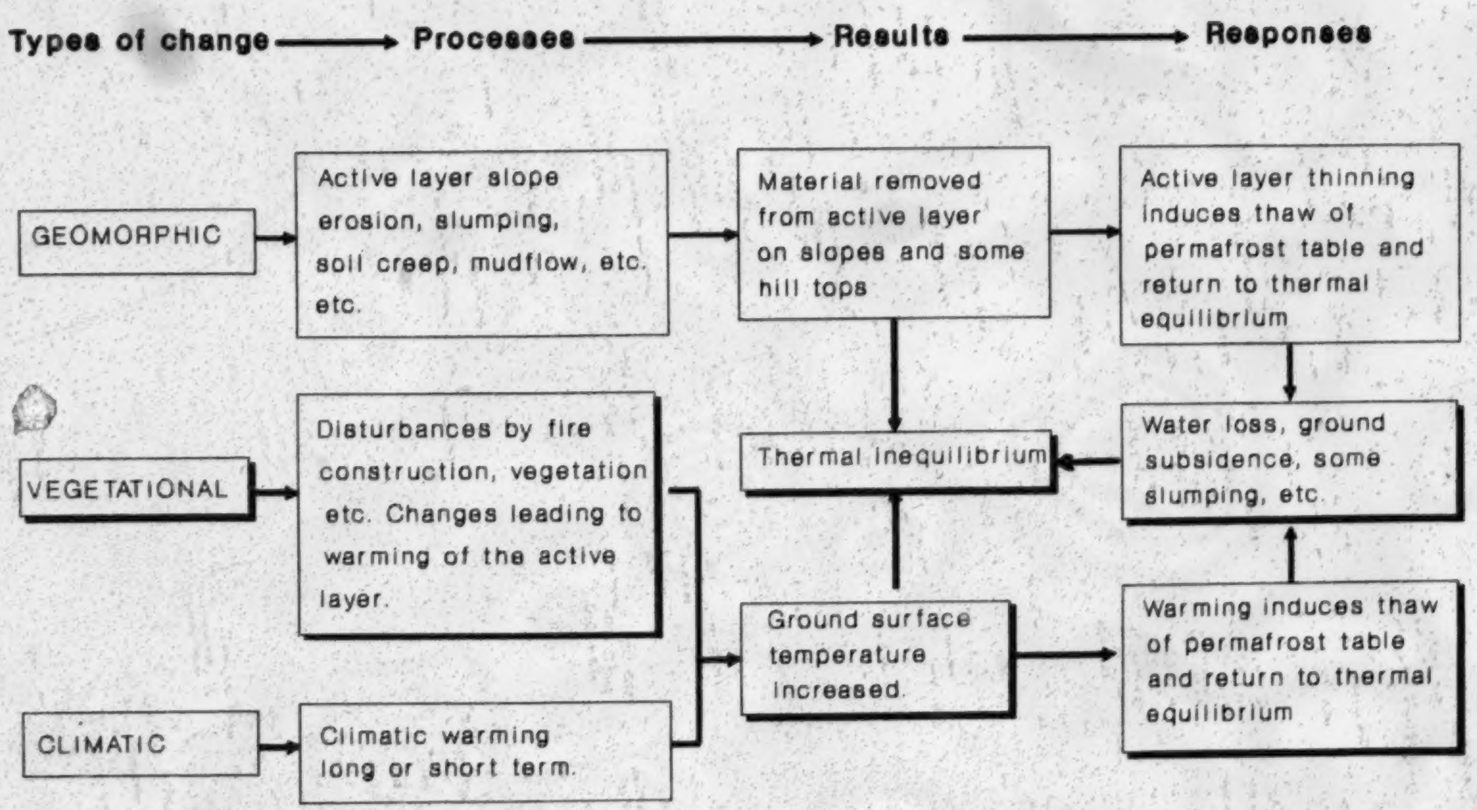

Types of change
Processes
Results
Responses
GEOMORPHIC
VEGETATIONAL
CLIMATIC
Active layer slope erosion, slumping, soil creep, mudflow, etc. etc.
Disturbances by fire construction, vegetation etc. Changes leading to warming of the active layer.
Climatic warming long or short term.
Material removed from active layer on slopes and some hill tops
Thermal inequilibrium
Ground surface temperature increased.
Active layer thinning induces thaw of permafrost table and return to thermal equilibrium
Water loss, ground subsidence, some slumping, etc.
Warming induces thaw of permafrost table and return to thermal equilibrium

Figure 4.15 Terrain responses at the SEEDS site based on Mackays (1971) process-response flow chart for arctic terrain following surface disturbance. Terrain responses at the site are indicated by shaded boxes.

SUMMARY OF STATISTICAL TESTS

Objective 1:
To determine if the intensity of the original disturbance effects the mean thaw depth and rates.

HO1 No significant differences exist in **(A)** the active layer thickness, and **(B)** the rates of thaw among the undisturbed control areas, rights-of-way, and a simulated pipeline trench as a result of human-induced perturbations.

HO1 (A) rejected
HO1 (B) rejected

Objective 2:
To determine if the mean thaw depth and thaw rate in each individual disturbance level varies over time.

HO2 No significant differences exist in **(A)** the active layer thicknesses, and **(B)** rates of thaw of the control, rights-of-way, and the trench over the three seasons of thaw.

HO2 (A) rejected
HO2 (B) rejected

Objective 3:
To determine if the length of time since the original disturbance had any significant effect on the thaw depths and rates.

HO3 No significant differences exist in **(A)** the active layer thicknesses, and **(B)** rates of thaw associated with surface disturbances of different ages.

HO3 (A) accepted for 1-year-old trenches
and 2-year-old rights-of-way
HO3 (B) accepted

Objective 4:
To determine the effect of insulation and revegetation treatments on trench thaw depths.

The insulation treatments conducted on the simulated pipeline trench did result in shallower thaw depths. After four thaw seasons there has been insufficient revegetation to have a recognizable effect on the thaw depth.

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CHAPTER 5: THERMOKARST SUBSIDENCE AND TERRAIN MODIFICATION RESULTING FROM HUMAN-INDUCED PERMAFROST DEGRADATION

INTRODUCTION

Numerous case histories of permafrost terrain disturbance have been documented throughout the Arctic and Subarctic regions (French, 1975; Kerfoot, 1973: Kurfurst, 1973; Lawson et al., 1978; Lawson, 1982; 1986; Mackay, 1970; among others). Most surface disturbances result in a modification of the difference between the average annual air and ground surface temperature. Ground temperatures rise in proportion to the increase in the mean annual ground temperature (Lachenbruch, 1970). Mackay (1970) states that this temperature change results from the disruption of the thermal equilibrium due to an alteration in either the geomorphic, vegetational or climatic conditions of the site.

Ground ice contributes significantly to the evolution and modifications of periglacial landscapes (Rampton, 1974). Disturbance can lead to pronounced geomorphic changes especially those produced by the degradation of ground ice and changes in the active layer (Bliss and Wein, 1973; Ferrains et al., 1969; French, 1974, 1975; Heginbottom, 1971; Kerfoot, 1973; Johnston, 1981; Zoltai and Pettapiece, 1973).

The thermal disequilibrium created by disturbance of the near-surface permafrost will produce a thickening of the active layer and a change in soil volume. The transition of ice to water involves a volume decrease of 9% and if the soil is saturated, the soil should decrease its bulk accordingly (Williams, 1982). Volume changes result from both the phase change, the flow of excess water from the soil and the internal consolidation of the soil structure (Harlan and Nixon, 1978). The volume change of the ice in addition to thaw consolidation can lead to the depression of the surface known as thermokarst (Lunardini, 1981). Muller (1947:223) defined thermokarst as "comprising karst-like topographic features produced by the melting of ground ice and the subsequent settling or caving of the ground."

The annual melting of the active layer will not produce thermokarst, as this occurs every year and the terrain has adjusted to these annual effects. The minor settling of the surface in summer is generally offset by frost heaving of the surface in winter. However, the thermal disequilibrium created by terrain disturbance may lead to substantial thermokarst subsidence, slope instability and the potential for fluvial and thermal erosion (Burns and Friele, 1989; French, 1974; Isaacs and Code, 1972; Kerfoot, 1973; Kurfurst, 1973; McRoberts and Morgenstern, 1974, Mackay 1971; Strang, 1973; and Viereck, 1982).

Thermokarst may develop in response to both local and regional environmental changes. Considerable north-south changes in the distribution of permafrost in the Mackenzie Valley over the last 150 years has been reported by Mackay (1975). On a regional scale, thermokarst resulting from climatic change is most often associated with the discontinuous permafrost zone where the thermal equilibrium is delicate (Lachenbruch _et al_., 1966). Changes in the southern boundary of this zone have resulted in the local development of thermokarst landforms and the disappearance of ice wedges, palsas and peat plateaus from Alaska (Pewe, 1966), palsas in the Mackenzie Mountains, Yukon (Kershaw and Gill, 1979) and the northern Prairie provinces (Thie, 1974; Zoltai, 1971).

However, thermokarst can occur under stable climatic conditions in response to a variety of geomorphic and or vegetation cover changes, whether naturally occurring or human-induced. Thermokarst resulting in such situations is commonly confined to the site of occurrence and immediately adjacent areas. Common causes of such disturbances include vegetation removal, erosion or excavation of surface materials, forest fires, and drainage modification.

Thermokarst processes, whether natural or human-induced, are considered to be amongst the most geomorphologically important and dynamic processes operating in the North (French, 1974; Heginbottom and Carter, 1987; Selby, 1985;

Sequin and Allard, 1984). Rapid and widespread landscape modification resulting from thermokarst processes has been reported from throughout the northern regions including: Siberia (Are, 1972; Czudek and Demek, 1970; Jahn, 1986), Mackenzie Valley (Issacs, 1974; Kurfurst, 1973; McRoberts and Morgenstern, 1974), Mackenzie Delta (Bliss and Wein, 1971; Mackay and Matthews, 1983; Mackay, 1970, 1986), and Alaska (Lawson, 1982, 1986; Linell, 1973; Nelson and Outcalt, 1982; Rickard and Brown, 1974).

The character and extent of geomorphological change associated with the thermokarst process depends on the properties of the terrain, the thermal and hydrologic regimes and the specific nature of the disturbance. The critical terrain response variables being the magnitude of the active layer increase and the amount of water/ice lost from the soil which in turn, depends on the increase in the ground surface temperature (French, 1976; Heginbottom, 1973; Kurfurst, 1973; Lawson and Brown, 1979). The amount of subsidence is primarily determined by the distribution and amount of ground ice. The processes of thaw settlement and consolidation are minimal in sediments where ground ice is limited and evenly distributed (e.g. pore ice). Because the release of excess water is limited there is little change in ground stability upon thawing. The most pronounced surface modifications have been reported from thaw-unstable, fine-textured sediments containing large volumes of excess ice (e.g. segregated ice)

(Brown and Grave, 1979; Kurfurst, 1973; Lawson, 1982; Mackay, 1970).

On flat terrain, increased thaw depths result in a general but uneven settlement of the ground surface resulting from the escape of meltwater and the thaw consolidation of the soil mass (Lawson, 1983; Mackay, 1971; Zoltai and Pettapiece, 1973). If degradation occurs slowly and if the drainage is not impeded, the meltwater will migrate from the thaw zone at the same rate as it is generated. This results in a gradual surface subsidence which proceeds at the same rate as the thawing (Harlan and Nixon, 1978; Morgenstern and Nixon, 1973).

When the meltwater resulting from permafrost degradation is generated at a faster rate than drainage permits, the excess pore pressures created can lead to intensified settlement and the instability of slopes. The potential for mass wasting in the permafrost zone is thus accentuated because thawed sediment can flow on very low-angled slopes (5° - 15°) (Harris, 1981; Morgenstern and Nixon, 1971), much lower than the angle of repose for dry unfrozen materials. Widespread slumping associated with natural and human-induced disturbances is common throughout the North (French and Egginton, 1973; McRoberts and Morgenstern, 1974, Morgenstern and Nixon, 1971). The alteration, ponding and concentration of surface runoff can result in changes in the thermal regime and promote further ground subsidence creating a negative feedback situation (Mackay, 1970; Lawson, 1982, 1986).

Thermal and mechanical fluvial erosion, resulting from the channelization of runoff, has been shown to be extensive along linear disturbances although little quantitative work has been carried out (Berg et al., 1978; Harlan, 1974, 1975; Kerfoot, 1973; Mackay, 1971, 1981; Nelson and Outcalt, 1982; Watmore, 1969).

From an applied viewpoint, thermokarst resulting from such perturbations represents some of the most serious engineering and environmental problems occurring in the permafrost regions. Subsidence of the buried portions of the IPL pipeline (Wishart, 1988; Wishart and Fooks, 1985) and the Trans-Alaska pipeline (Thomas and Ferell, 1983) has been one of the most extensive problems to date. As such, the prevention and or control of thermokarst is a major challenge for northern development especially where the integrity of the ground surface is critical as it is with pipelines.

RESEARCH OBJECTIVES

While the first paper deals with the initial phase of thermokarst processes resulting from human-induced disturbances, specifically the impact on the thickness of the active layer and the degradation of the near-surface permafrost, this second paper deals with the subsequent alterations of microtopography due to thermokarst subsidence and other short-term surficial modifications.

The magnitude of the detrimental effects of increased thawing is highly variable, and is related to the ground ice content and the severity of the original disturbance at the ground surface. Lawson (1986) grouped the types of disturbances associated with the multiplicity of northern exploration and development activities according to the physical modification they caused (Appendix 1). The initial impacts to the vegetation, soils and sediments range from the least intensive (trampling and compaction of the organic mat) to the most intensive (removal of the near-surface sediments with the organic mat).

The experimental disturbances at the SEEDS site reflect this increasing level of intensity. The control data from the undisturbed _Picea mariana_-dominated forest sites serve as baseline information defining the natural variability of the parameters in question against which changes associated with the disturbance can be compared. The hand-cleared ROWs represented the intermediate level of disturbance, simulating corridors created for seismic, winter road, power transmission line, and pipeline rights-of-way. The excavated and backfilled trench represented a more intensive disturbance similar to those created by bladed trails and buried pipelines.

The primary effects of these and other disturbances involve changes in the insolation, albedo, evapotranspiration, thermal conductivity of the organic mat, snow accumulation and drainage patterns (Haag and Bliss, 1974a, 1974b; Isaacs and Code, 1972; Linell and Tedrow, 1981). The overall effect at the SEEDS site has been to produce an increase in the mean annual ground temperature which results in the degradation of the near-surface permafrost and a thickening of the active layer. The amount of thermokarst subsidence and other degradational processes following terrain disturbance has been shown to be related to the extent of permafrost degradation thus leading to the objectives of this study:

Objective 1:
To determine whether or not the severity of disturbance and the subsequent extent of permafrost degradation will have an effect on the magnitude of thermokarst subsidence.

Objective 2:
To determine whether or not other short-term degradational processes related to thermokarst subsidence (fluvial and/or thermal erosion, and gravitational slope processes) will operate on the site to cause topographic modifications.

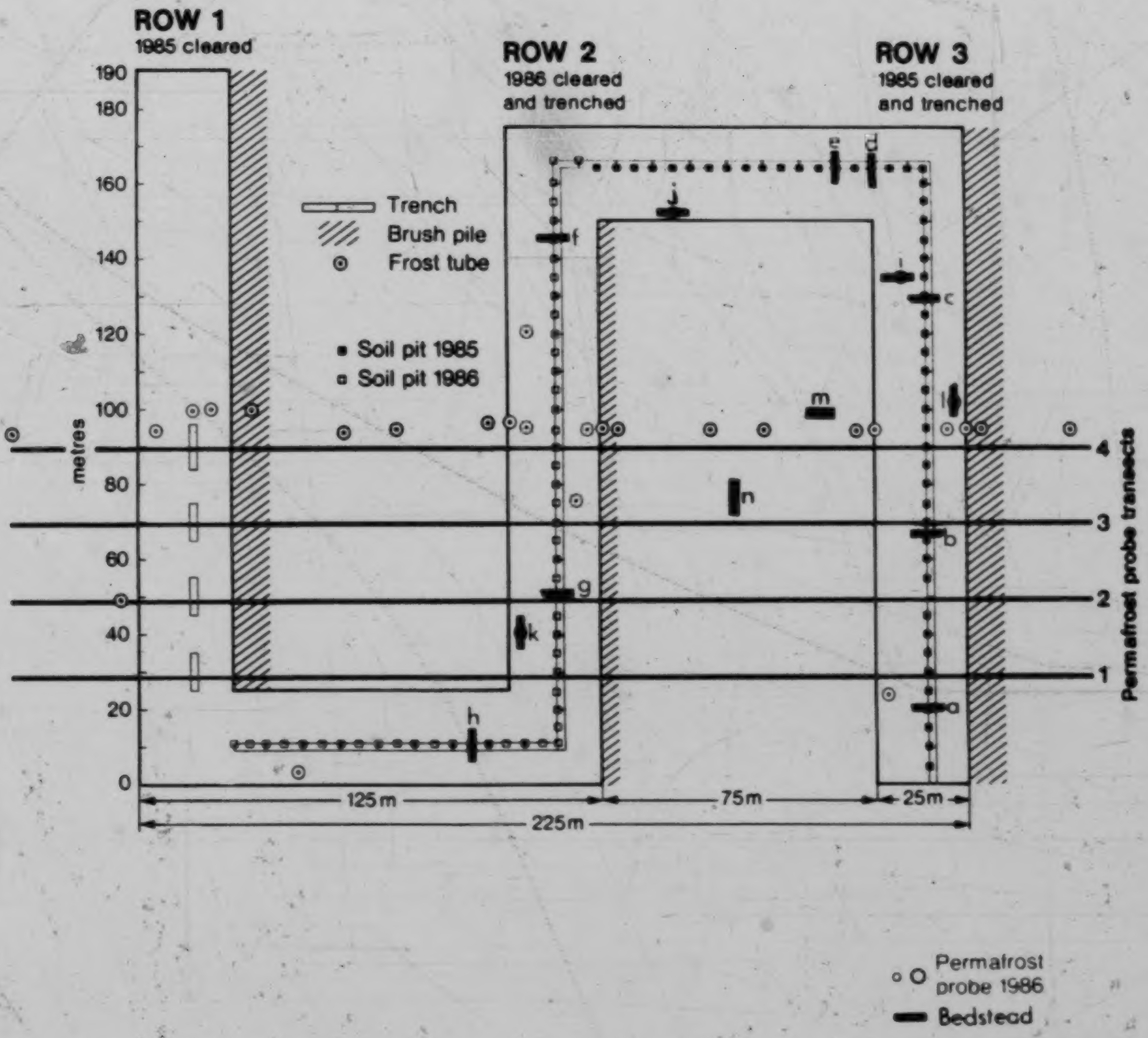
FIELD METHODS

The major component of this portion of the project involved detailed quantitative measurements of relative and actual changes in microscale relief, with an emphasis on thaw subsidence. A modified 'Schefferville' bedstead (Andrews, 1963; Haywood, 1963; Fahey, 1973; Matthews, 1963; Smith, 1988) was used for the determination of the micro-scale soil displacements. The original bedstead design (June 1986) consisted of a 3 m by 1.5 m frame which would have allowed for the three dimensional contour mapping of the soil surface. This design proved too inaccurate because of logistical and levelling problems.

The design format eventually selected consisted of a single 3 m transect. Pairs of 1.8 cm diameter wooden dowels (2 m apart) were anchored into the permafrost (to depths of 2.25 m) to serve as fixed supports against which surface elevations could be referenced. A 3 m section of vinyl downpipe (6.5 cm square) suspended between the support posts. Each downpipe was then drilled with 29 holes (10 cm apart) into which wooden dowels were inserted (1.2 m long and 0.8 cm diameter). Surface topography along the transect was determined by resting all of the dowels on the ground surface and measuring the length of dowel protruding above the frame. All measurements were recorded to the nearest millimetre. The lack of a permanent survey bench mark in or near the SEEDS site prohibited the tieing in of all bedstead elevations, therefore the soil displacements that were determined were relative values, based on the magnitude of surface elevation change experienced at each site.

Fourteen bedstead monitoring stations were constructed and installed throughout the site (excluding ROW 1) in May and early June of 1987 (Figure 5.1). Eight were randomly located along the ROW 2 and ROW 3 simulated pipeline trenches. Five were within the trench excavated in 1985 and 3 within the trench excavated in 1986 (Plate 5.1). Four additional bedsteads were located on the rights-of-way (Plate 5.2) and two were in the undisturbed 'control' forest (Plate 5.3).

Bedstead measurements were taken at regular weekly intervals during the 1987 thaw season (May 21 to August 26, trench and ROW sites). An important point to note is that the control bedsteads were not established and operational until approximately one month later (June 17) than the trench and ROW bedsteads. The 1988 season lasted from May 11 to August 31. Measurements for the trench sites extended 2 m from one side of the trench to the other and included 0.5 m of ROW on either side. In addition to measurements of the surface topography, the seasonal position of the permafrost table below the bedstead was determined through frost probe readings every 50 cm.


ROW 1
1985 cleared
ROW 2
1986 cleared
and trenched
ROW 3
1985 cleared
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190
180
160
140
120
100
80
60
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0
metres
Trench
Brush pile
Frost tube
Soil pit 1985
Soil pit 1986
a
b
c
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h
i
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l
m
n
125m
75m
25m
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4
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Permafrost probe transects
Permafrost probe 1986
Bedstead

Figure 5.1 Location of the bedstead ground surface monitoring stations, SEEDS site, 1987 to 1988.

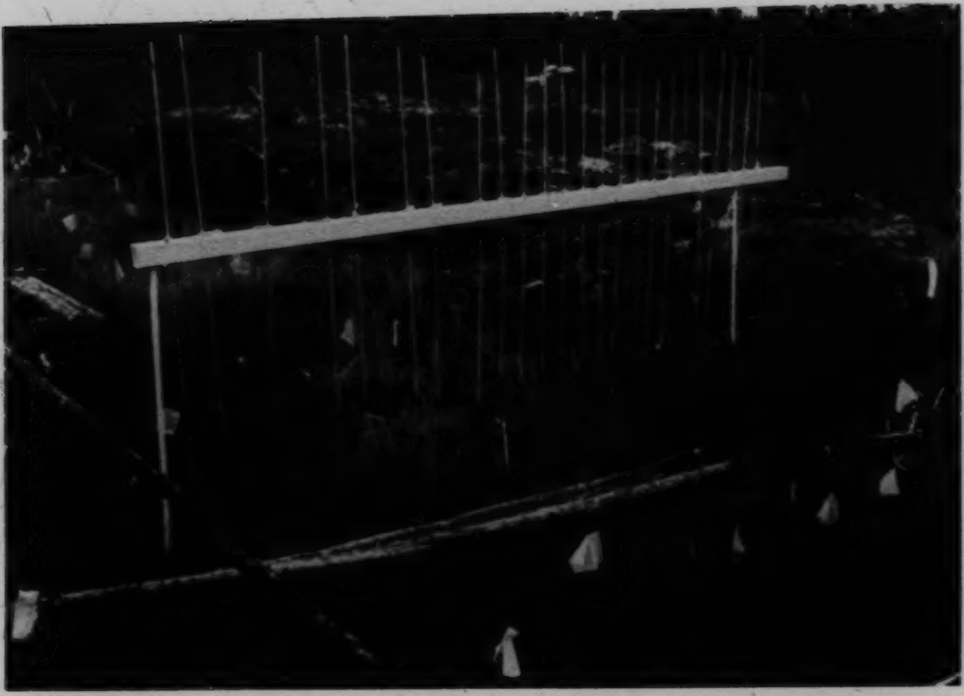


Plate 5.1 Bedstead B - an example of a bedstead located on the excavated and backfilled simulated pipeline trench. Row 3, July 1988.

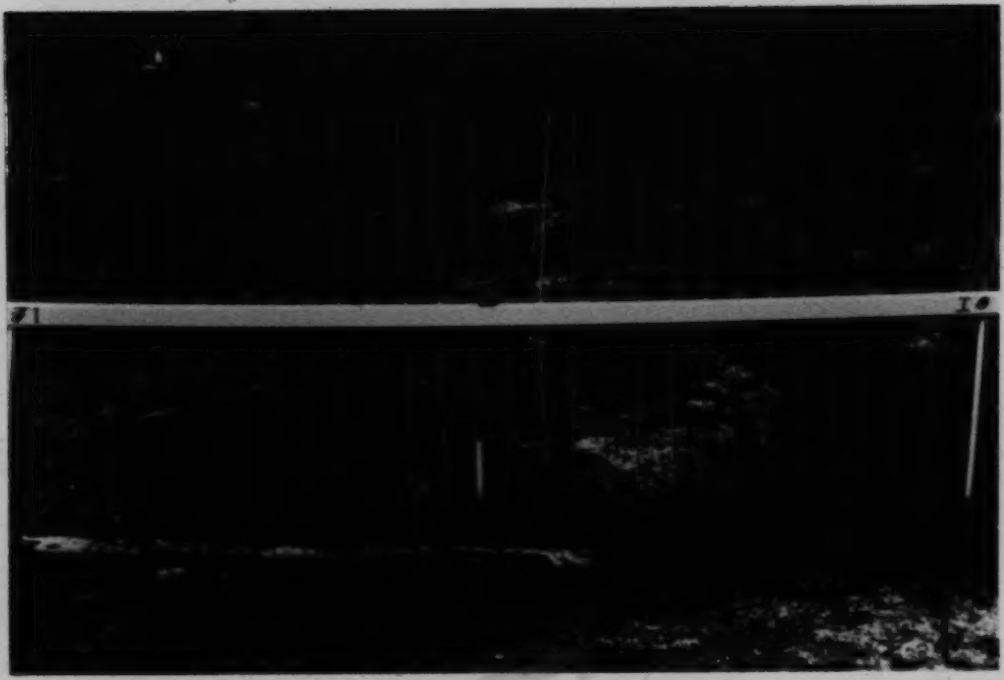


Plate 5.2 Bedstead I - an example of a bedstead located on the northern end of ROW 3, June 1987. Associated frost tube can be seen in the center of the photo.

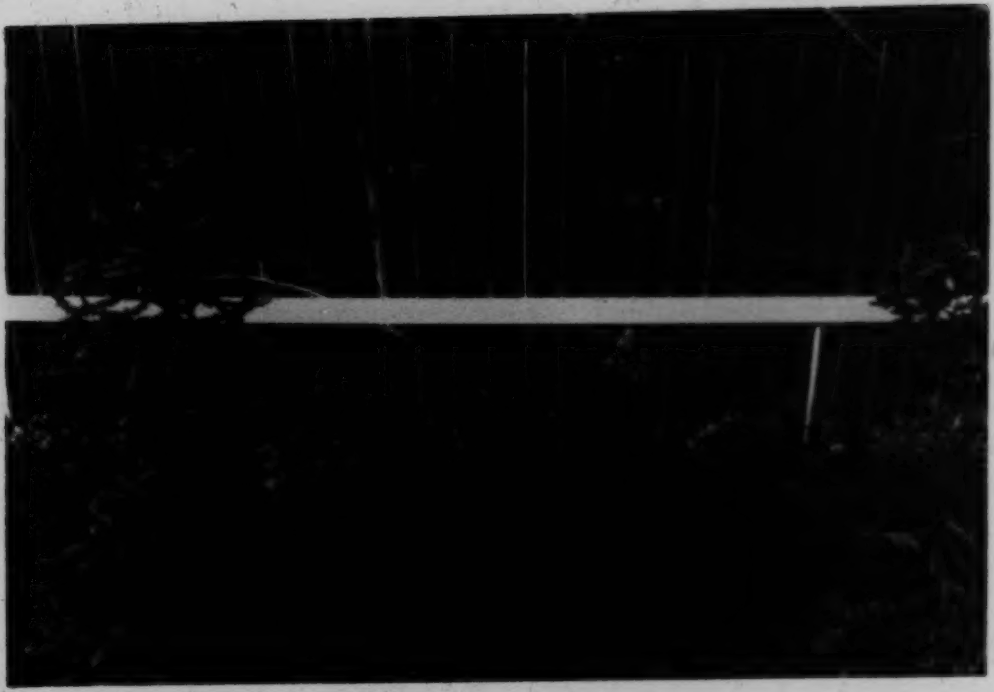


Plate 5.3 Bedstead N - an example of bedstead located in the undisturbed control, June 1987.

The possibility of frost heaving of the bedstead support posts prevented the determination of cummulative subsidence over the two-year-period. New base height datums were established for each bedstead, and because these elevations varied from site to site the subsidence values were transformed in order to standardize them to a common bedstead elevation.

Evidences of other degradational processes were also examined. The presence and depth of water within the trench was recorded in order to delineate the location and timing of ponding or channelized flow. Surface and subsurface trench discharge and subsurface ROW discharge measurements were recorded from the ROW 3 fluvial monitoring station (Gallinger and Kershaw, 1988). Surface compaction, gravitational slope processes and fluvial activity (erosional and depositional processes) were observed. Soil characteristics, including texture, moisture content by weight, ice content by volume and Atterberg limits were discussed in Paper 1.

RESULTS

General overview

Mean maximum values of the amount of relative displacement of the position of the ground surface and the seasonal active layer thickness, for two consecutive thaw seasons, were compiled (Table 5.1). Subsidence and thaw rates have been averaged over each thaw season. The surface settlements recorded by the bedsteads are probably minimum values, since for all of the sites the initial (1987) topographic surveys took place one (ROW 2) and two (ROW 3) thaw seasons following the clearance of the ROW and the trenching process.

Analysis of the thaw subsidence data indicates that significant variations occur in both the pattern and the magnitude of subsidence depending on the level of human disturbance, particularily in the first year of observation.

Average cumulative surface settlements, observed at each of the 14 bedsteads, were plotted for the 1987 and the 1988 (Figure 5.2) thaw seasons. While thaw settlement was obviously ongoing in 1988, the amount and rate were variable compared with the first year of observation. A comparison of the data from successive seasons indicates that the amount and rate of settlement associated with the trench sites was decreasing over time while the ROW and control sites experienced either similar or greater amounts of subsidence in the second season.

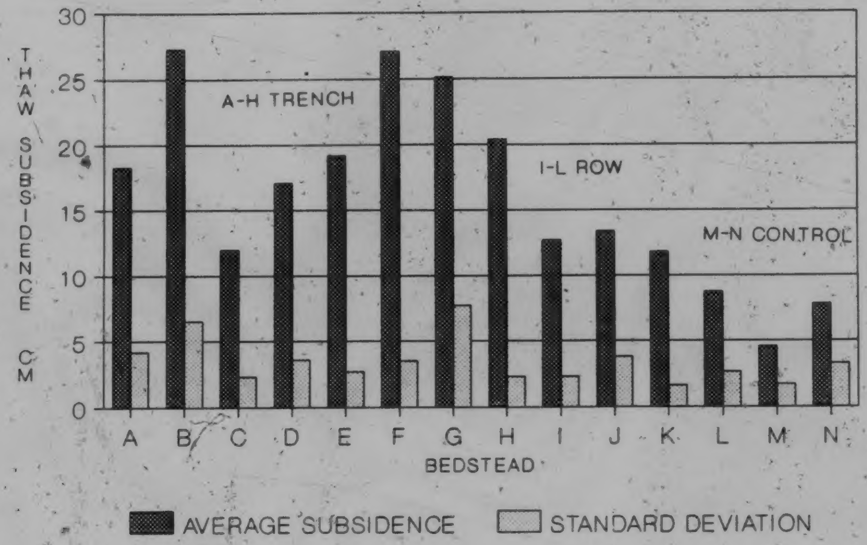
Table 5.1 Mean maximum thaw subsidence and rates, and mean maximum thaw depths and rates as determined at the control, ROW, and trench bedstead monitoring stations. Values for the 1987 and 1988 thaw seasons. Subsidence and thaw values expressed as cm and the rates as mm/day. Rates calculated on the basis of delta subsidence and thaw values.

1987 THAW SEASON	MAXIMUM SUBSIDENCE	SUBSIDENCE RATE	MAXIMUM THAW DEPTH	THAW RATE
CONTROL (n size)	56	56	14	14
MEAN	6.18	0.9	63.18	6.49
STAND. DEV.	3.09	0.4	6.25	0.64
ROW (n size)	114	114	28	28
MEAN	11.66	1.3	54.75	4.37
STAND. DEV.	11.66	0.4	5.16	1.32
TRENCH (n size)	237	237	56	56
MEAN	18.88	2.2	97.86	5.93
STAND. DEV.	8.41	0.7	21.54	2.47

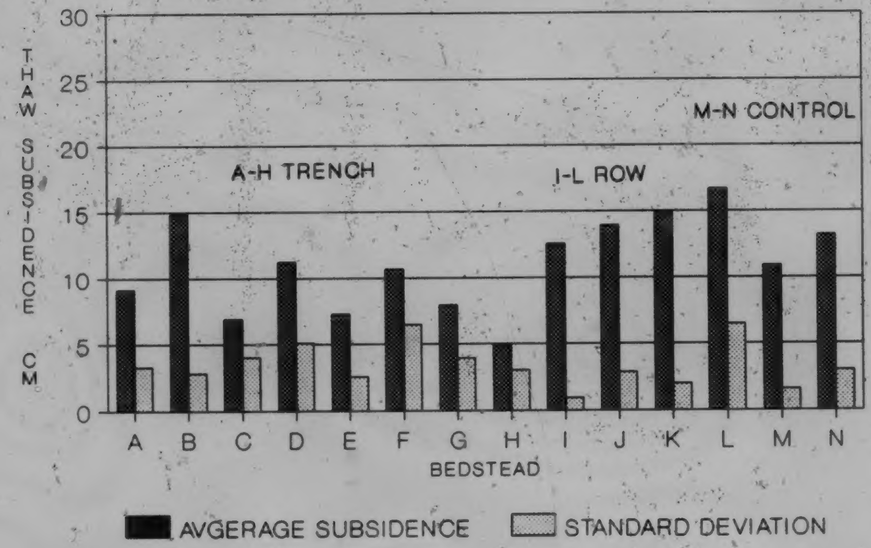
1988 THAW SEASON	MAXIMUM SUBSIDENCE	SUBSIDENCE RATE	MAXIMUM THAW DEPTH	THAW RATE
CONTROL (n size)	58	58	14	14
MEAN	12.12	1.07	70.69	5.46
STAND. DEV.	2.65	0.5	5.91	0.6
ROW (n size)	115	115	28	28
MEAN	14.59	1.29	66.75	5.32
STAND. DEV.	4.00	0.3	6.17	0.9
TRENCH (n size)	230	230	56	56
MEAN	9.15	0.81	126.88	9.91
STAND. DEV.	5.00	0.4	26.01	4.67

Monitoring periods:

1987 subsidence -	Control	June 17 - August 26 (70 days)
	Rights-of-way	May 21 - August 26 (97 days)
	Trench	May 21 - August 26 (97 days)
1987 thaw depths	all sites	June 20 - August 26 (62 days)
1988 subsidence & thaw	all sites	May 11 - August 31 (112 days)



AVERAGE SUBSIDENCE PER BEDSTEAD
1987 THAW SEASON



AVERAGE SUBSIDENCE PER BEDSTEAD
1988 THAW SEASON

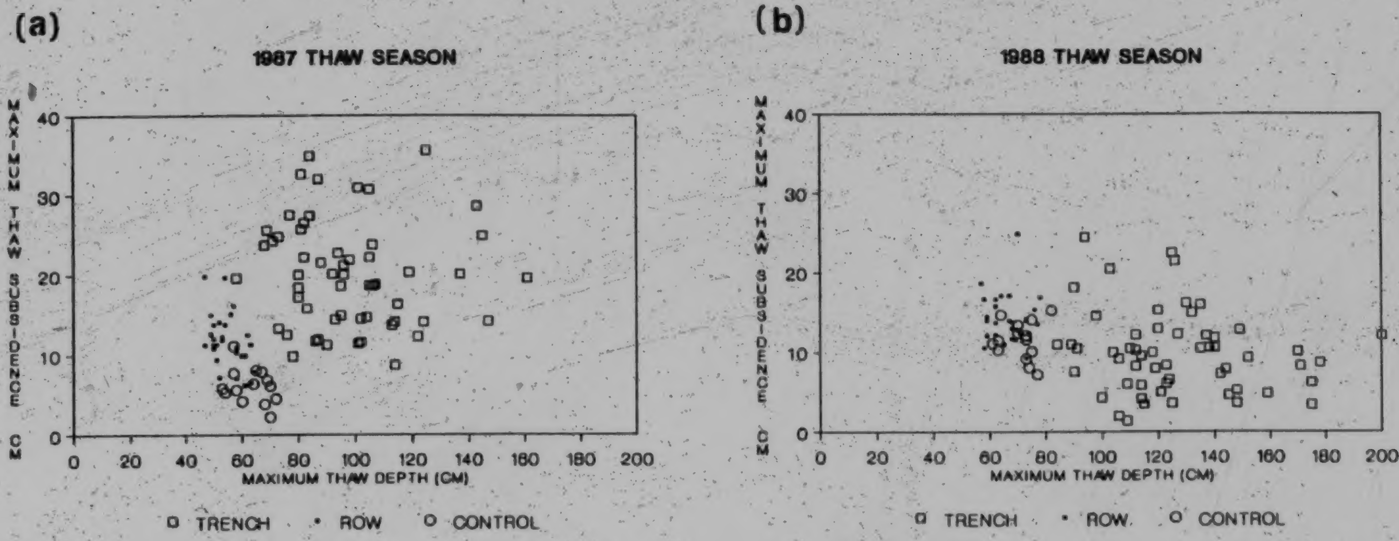
FIGURE 5.2 Average thaw subsidence per individual bedstead during the 1987 and 1988 thaw seasons.

Relationship between thaw subsidence and maximum thaw depth

A general relationship was found between maximum thaw depth and maximum thaw subsidence (Figure 5.3a and b). In the 1987 thaw season a general clustering of the data points from each disturbance level was noted, with the control sites displaying the minimum thaw depths (50 - 72 cm) and the minimum amount of thaw subsidence (2-12 cm), while the trench had much higher values of both thaw (60 - 160 cm) and subsidence (10 - 35 cm). The variability was least in the control and most in the trench. The ROW sites had narrow ranges for both the maximum thaw depth values (45 - 65 cm) and subsidence values (5-20 cm).

In 1988 the general pattern of maximum thaw depth versus thaw subsidence for each of the disturbance levels was similar. The most dramatic change was the decrease in the thaw subsidence values for the trench sites (3 - 25 cm), and an increase in the variability of the thaw depth values (84 - 200 cm). Control and right-of-way sites had similarily narrow ranges for both subsidence and thaw, however the subsidence values increased, 7 - 16 cm and 9 - 25 cm for the control and ROW, respectively.

THAW SUBSIDENCE VERSUS MAXIMUM THAW DEPTH



Trench bedsteads A to H

ROW bedsteads I to L

Control bedsteads M to N

Figure 5.3 Relationship of subsidence values and mean maximum thaw depth for the **(a)** 1987 and **(b)** 1988 thaw seasons.

TRENCH - BEDSTEADS A THROUGH H

In the 1987 field season, the most significant change in surface elevation occurred over the simulated pipeline trench, where the surface was lowered by an average of 18.9 cm (range 12 - 27 cm) between June and August, this was 143% greater than the thaw subsidence occurring under control conditions (assuming equal time periods). In the second year (1988) there was a dramatic decrease (106%) in the amount of trench subsidence. The maximum thaw depths, on the other hand, increased by 30%. Substantial variation in the magnitude of subsidence was noted between the trench bedstead sites (Figures 5.4 to 5.11). This differential settlement and variable thickness of the active layer (as noted by the high standard deviations) resulted initially in a highly irregular trench surface.

The position of the seasonal frost table became more defined as well as deeper in the second season, mirroring the U-shaped trench surface morphology. Mean maximum thaw depths in the 1988 thaw season averaged 127 cm, well below the zone of aggradational ice found under ROW conditions.

Bedsteads B, F, G, and H displayed considerably more subsidence than other trench sites. Of these sites, F, G, and H, were located on the portion of the trench that was excavated only one year before while the remaining sites were on a two-year-old disturbance. Growth and/or regrowth of native or agronomic species had not yet occurred on the ROW 2 and south link trench thus the surfaces were characterized by essentially exposed mineral and organic substrate. For a majority of the 1987 thaw season the sediments in these porticns of the trench were either saturated or completely underwater.

The portions of the trench bedsteads that extended onto the adjacent rights-of-way subsided almost as dramatically as the trench proper (16.3 cm versus 18.6 cm in 1987). Evidence of fluvial undercutting and slumping processes were noted along the trench margins. In addition to subsidence these lateral erosion processes helped to create less distinctive margins and in some cases caused the 2m-wide trench to become larger than the area originally disturbed. This was particularily noticable where the trench margins were steep and subject to mass-movement processes.

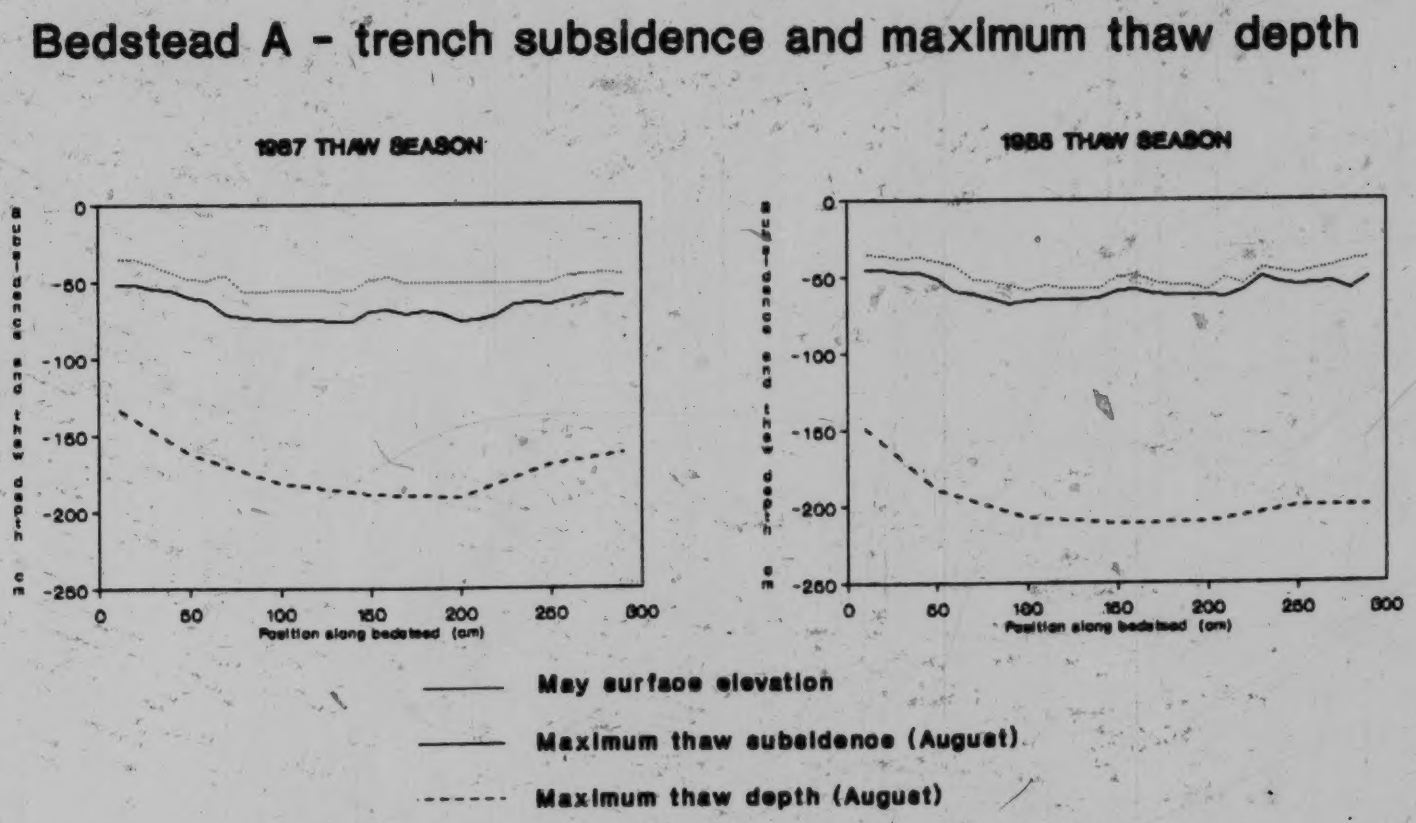


Figure 5.4 Trench bedstead A - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

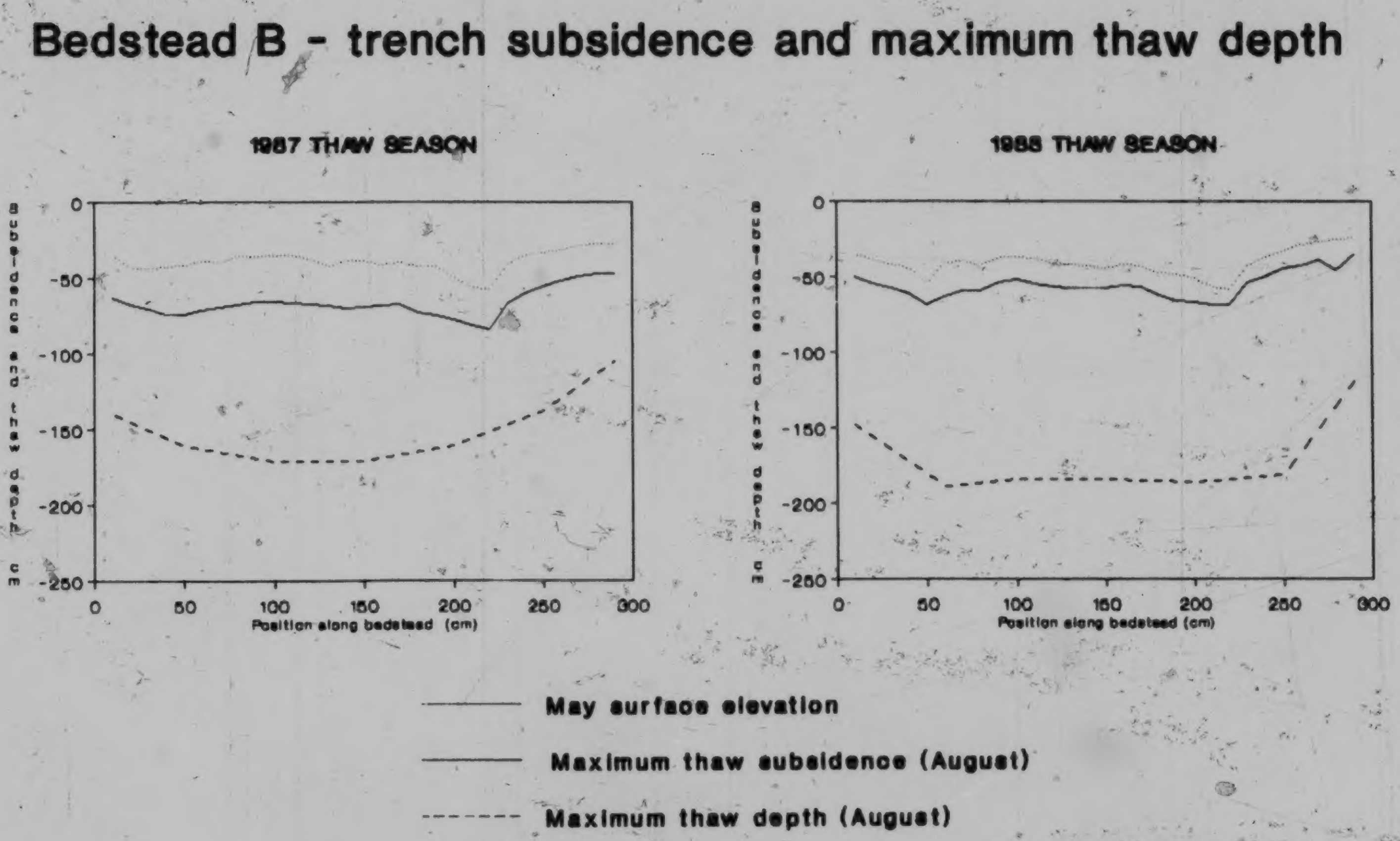


Figure 5.5 Trench bedstead B - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

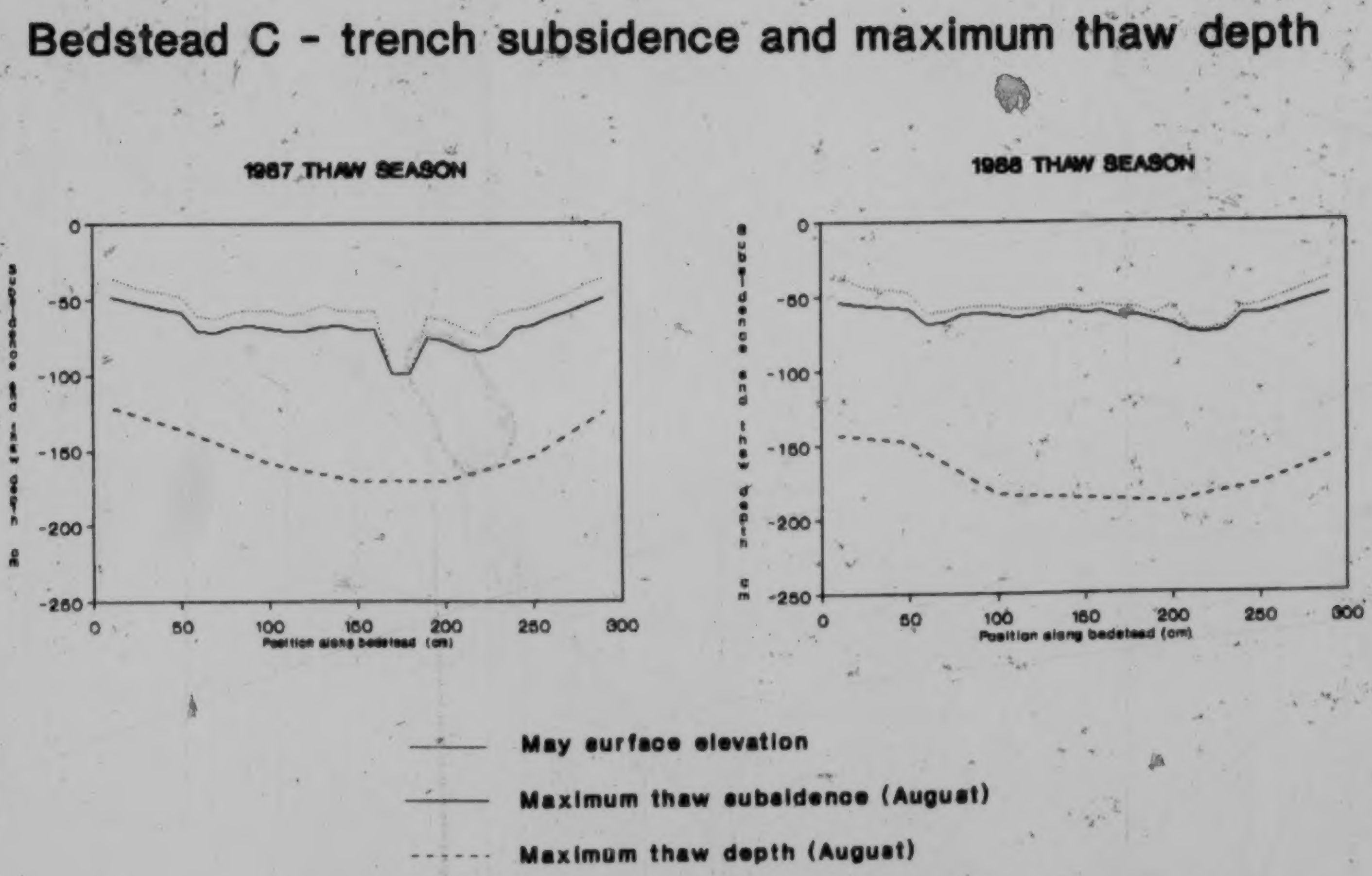


Figure 5.6 Trench bedstead C - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

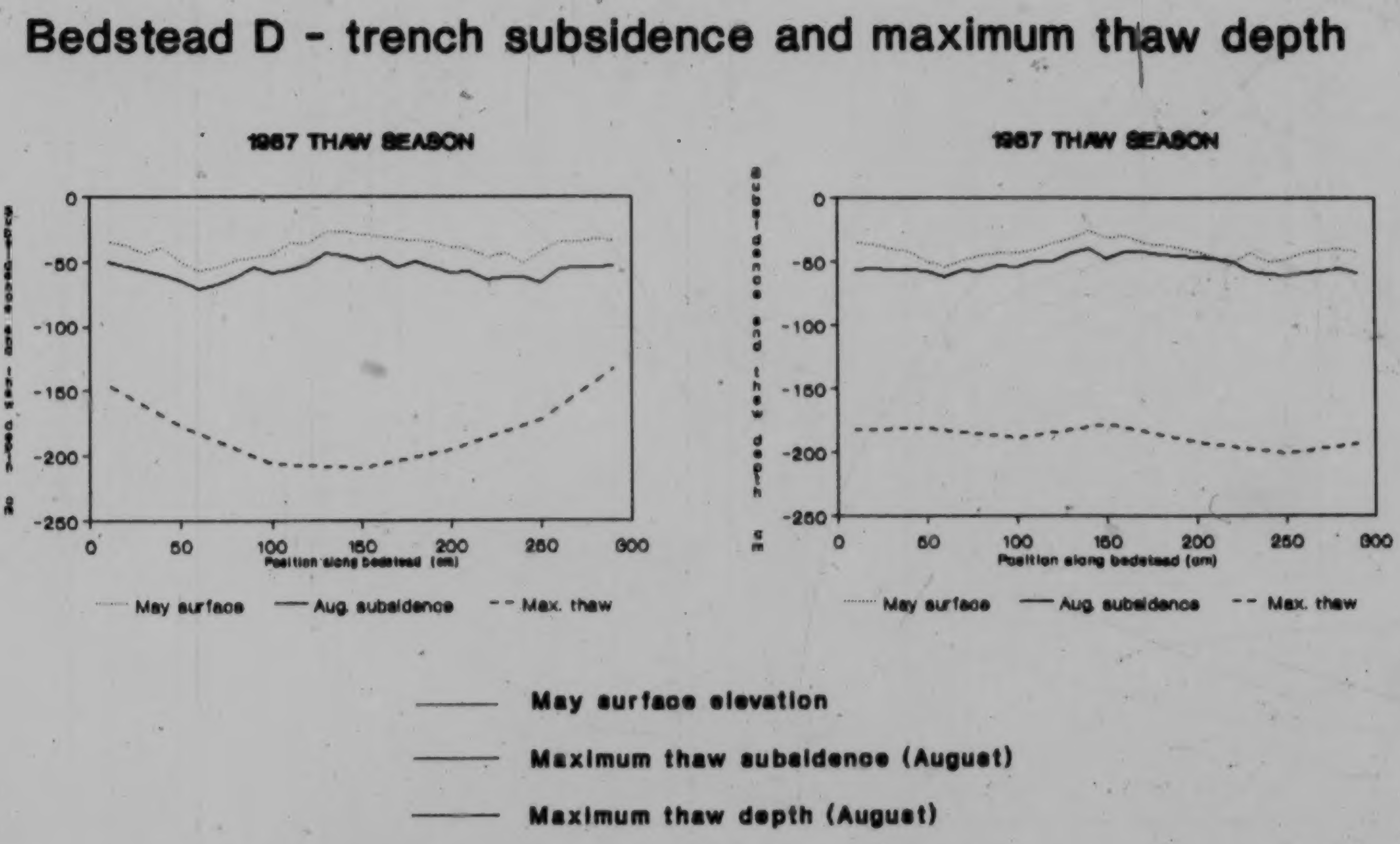


Figure 5.7 Trench bedstead D - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

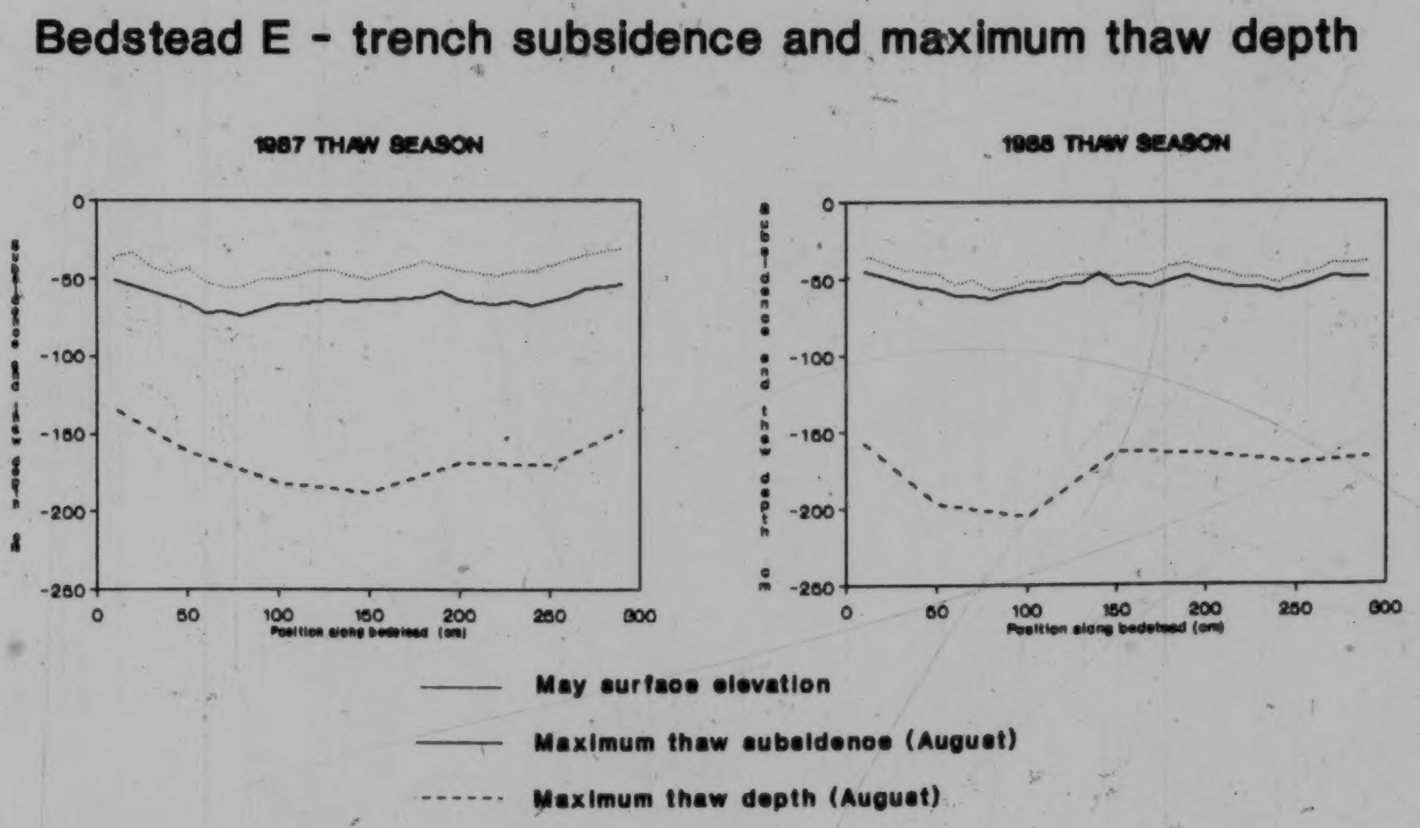


Figure 5.8 Trench bedstead E - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

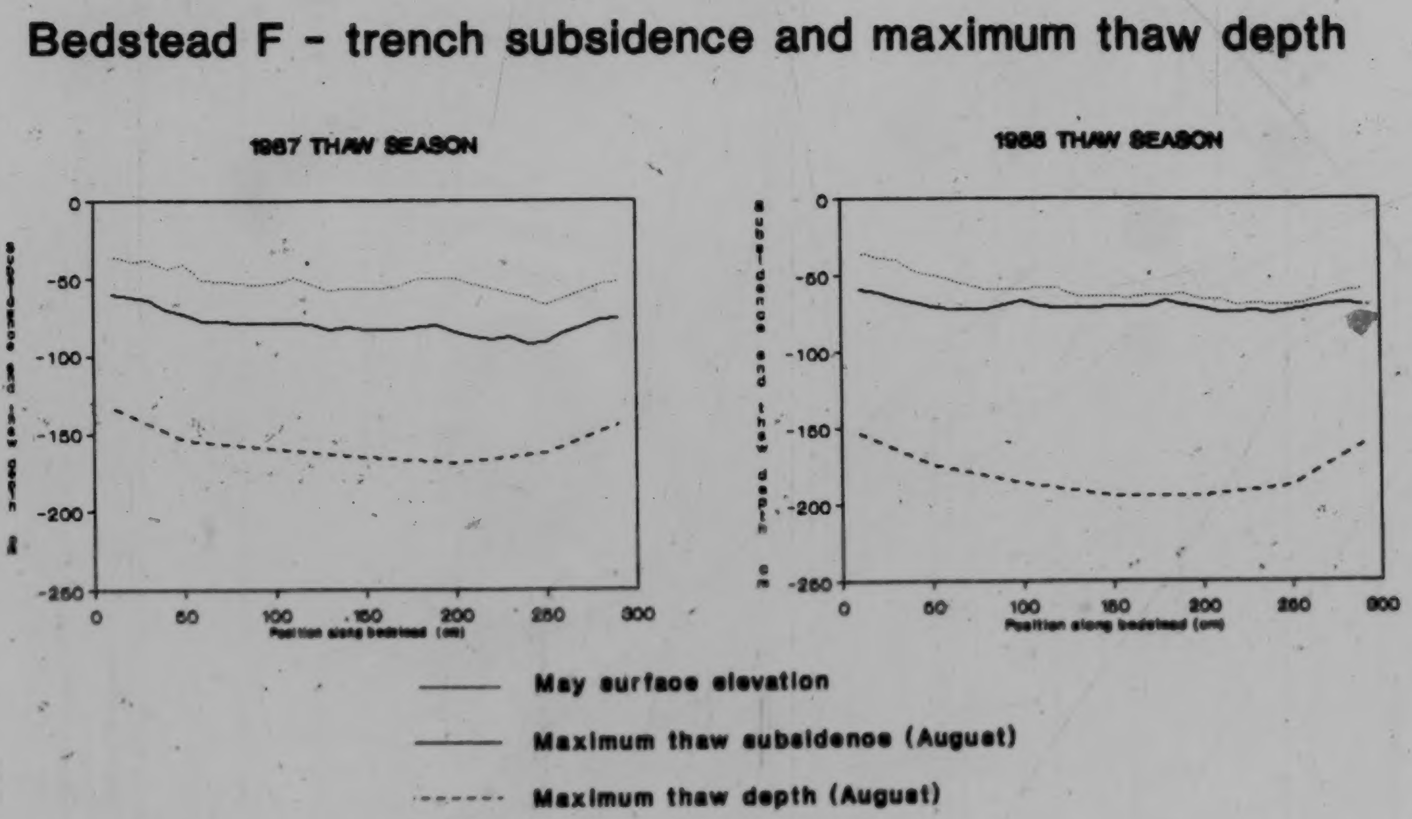
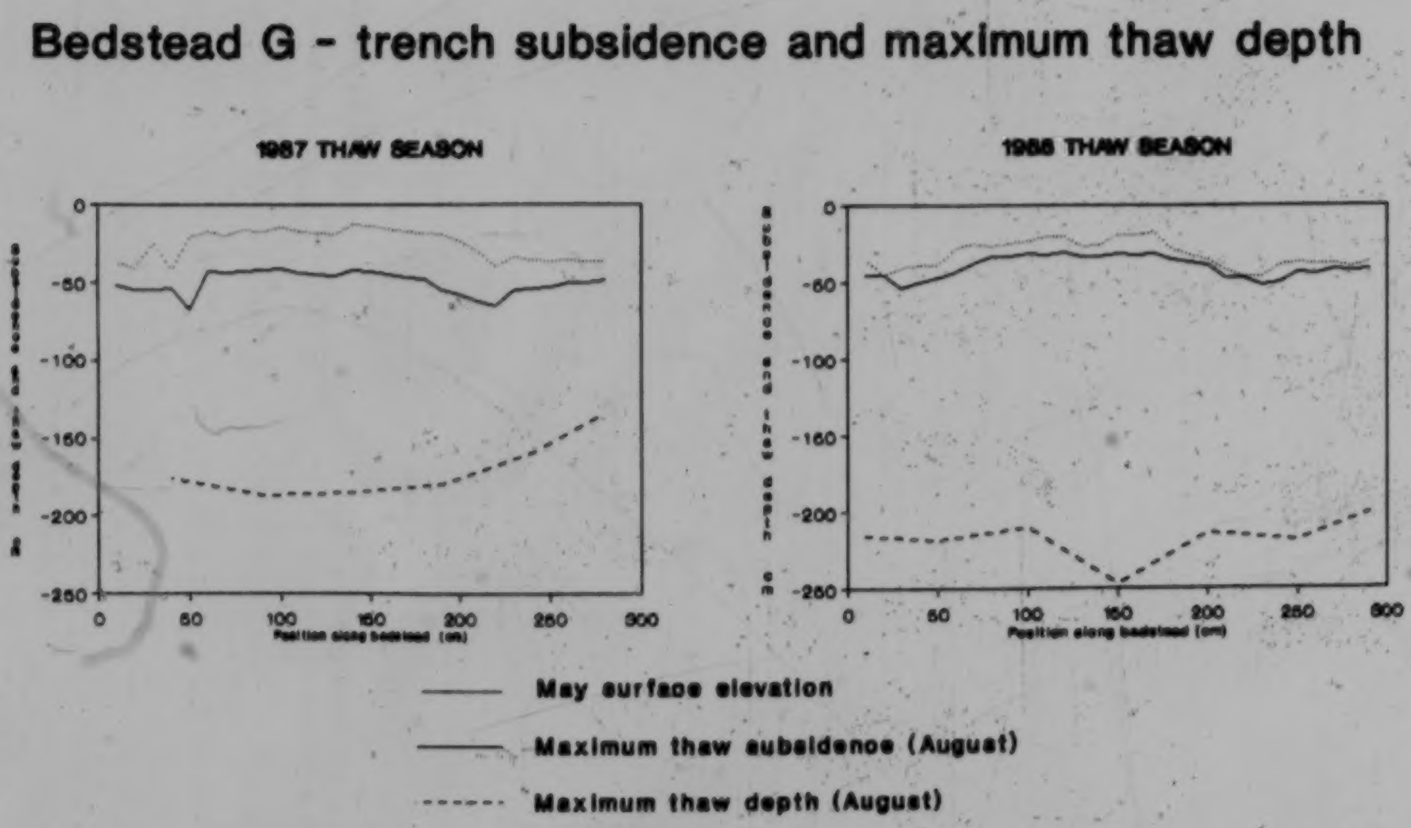


Figure 5.9 Trench bedstead F - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.


Bedstead G - trench subsidence and maximum thaw depth

1987 THAW SEASON

1988 THAW SEASON

Figure 5.10 Trench bedstead G - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end of the 1987 and 1988 thaw seasons.

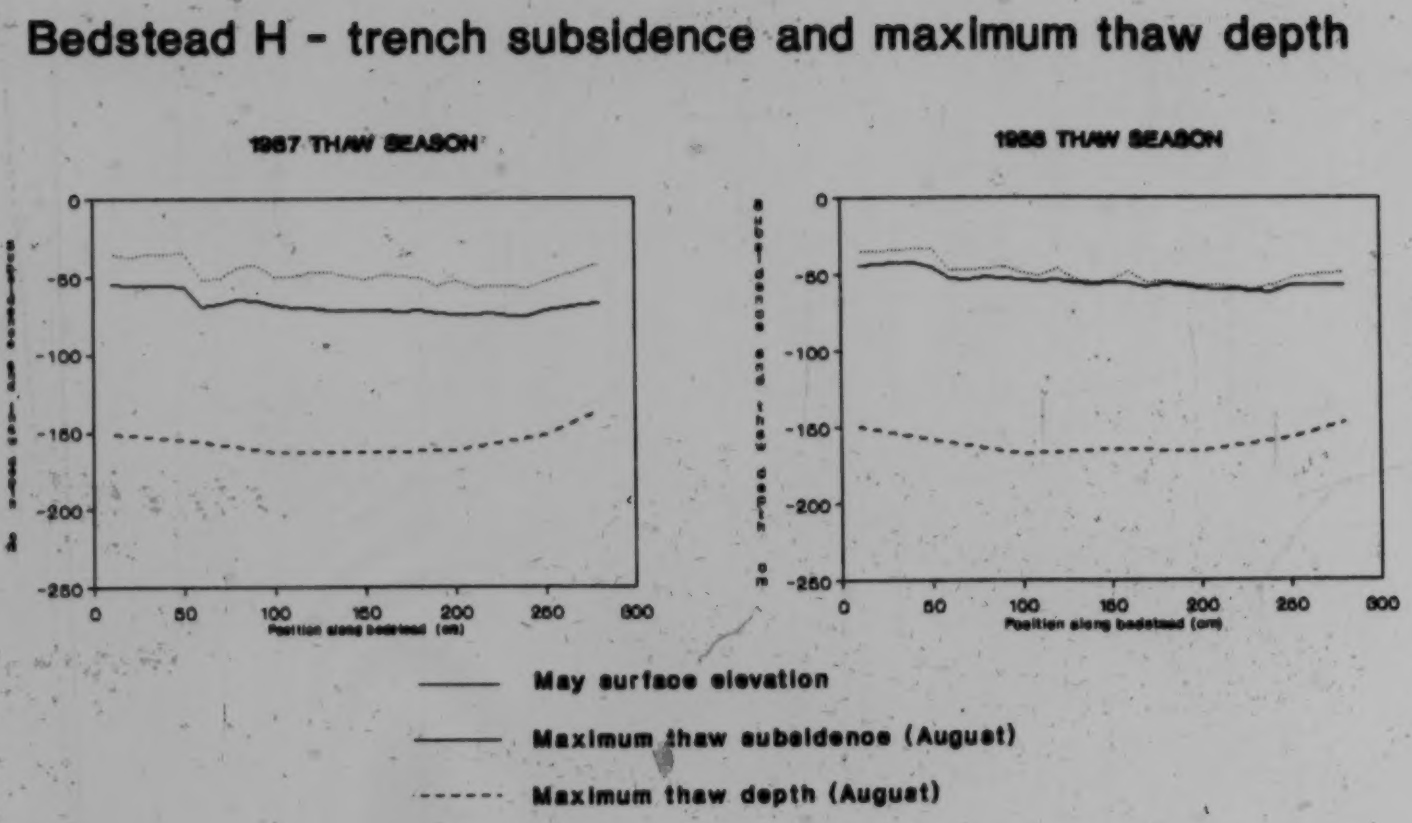


Figure 5.11 Trench bedstead H - intial surface topography and maximum thaw subsidence and maximum thaw depth at the end othe 1987 and 1988 thaw seasons.

RIGHTS-OF-WAY - BEDSTEADS I TO L

The amount of thaw subsidence occurring under ROW conditions averaged 11.66 and 14.54 cm for the 1987 and 1988 thaw seasons, respectively. ROW subsidence was 44% (1987) and 20% (1988) greater than that of the undisturbed control. In 1988, the ROW sites had the overall highest subsidence values, however the similarity in thaw subsidence rates (1.3 mm/day) suggest that the apparent settlement increase in the second season was the result of a slightly longer monitoring period (15 days earlier). Subsidence values in 1987 were likely restricted due to the shortness of the monitoring season (bedsteads were not operational until June 17).

Variable amounts of surface subsidence were observed under ROW conditions (Figures 5.12 to 5.15) resulting in the creation of a slightly more irregular surface topography by the end of each thaw season. Bedstead L provides a good example of this process with variations of micro-relief of 15 to 20 cm. Sites I, J, and K experienced slightly lower (18%) amounts of subsidence in the second observation season while subsidence at site L increased from 8.6 to 16.7 cm, an increase of 94%.

The seasonal permafrost table under the ROW bedsteads was generally level, paralleling the surface topography. The mean maximum thaw depth and thaw rate increased by 21% (54.75 cm to 66.75 cm) between the two years.

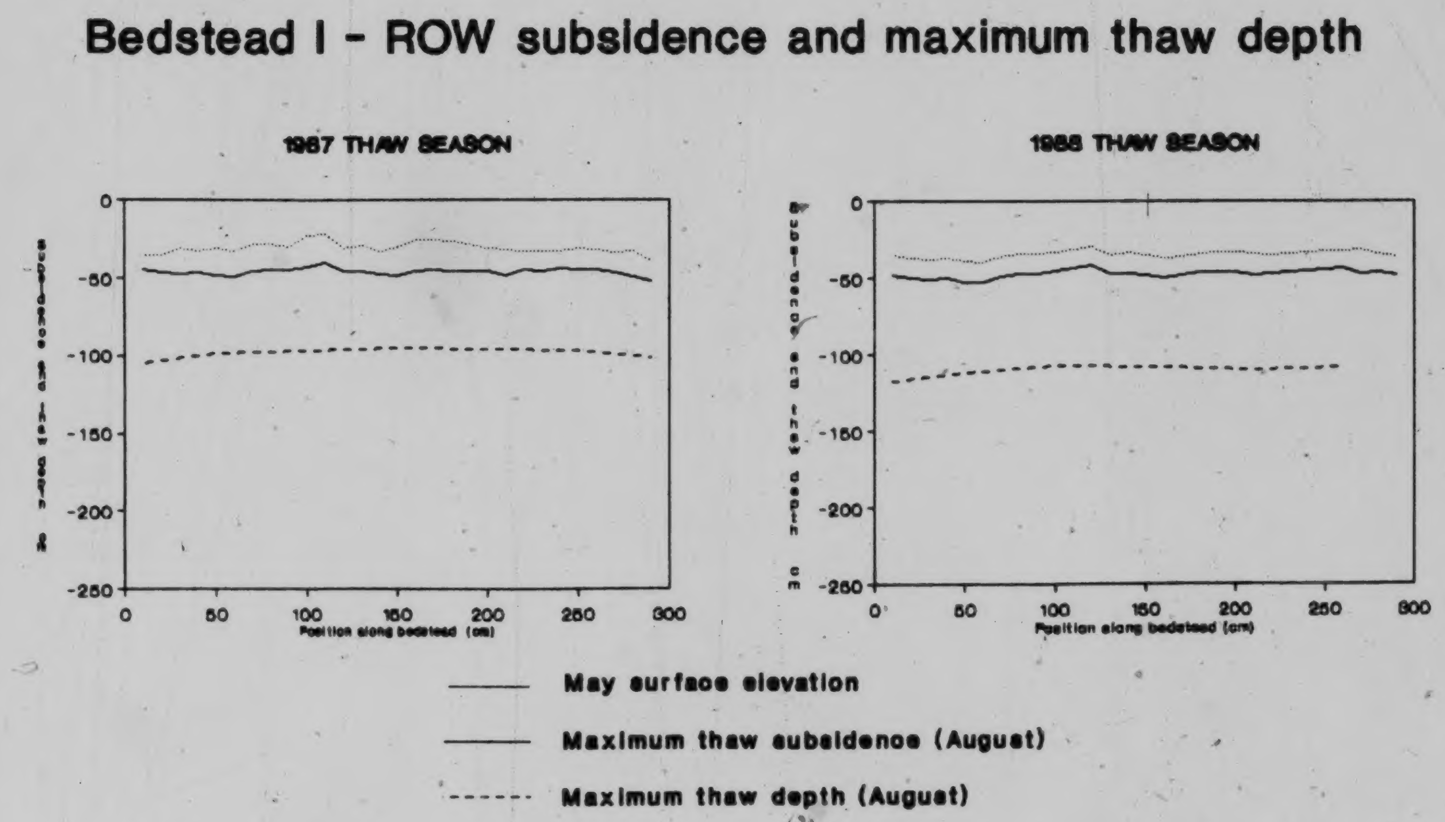


Figure 5.12 Right-of-way bedstead I - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

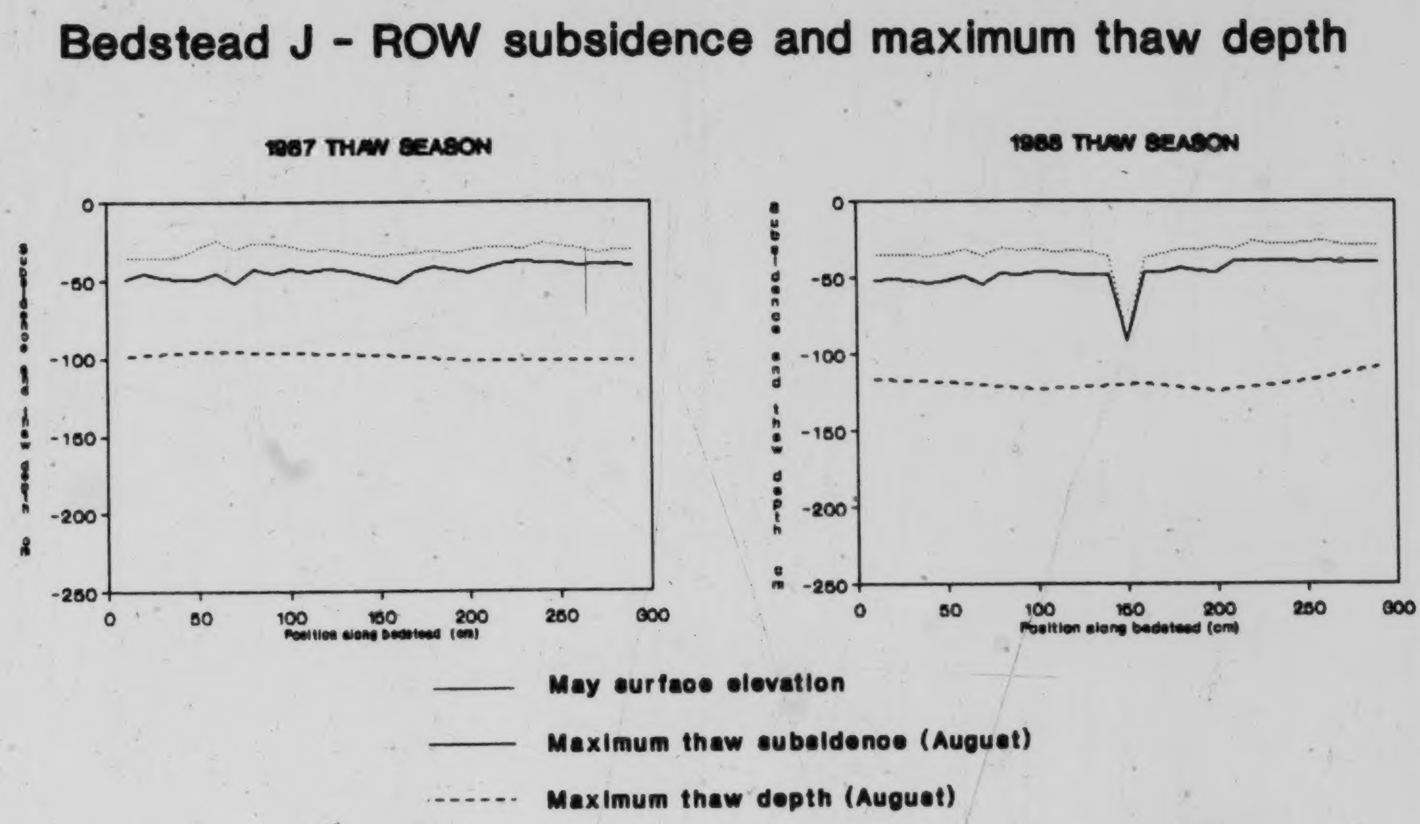


Figure 5.13 Right-of-way bedstead J - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

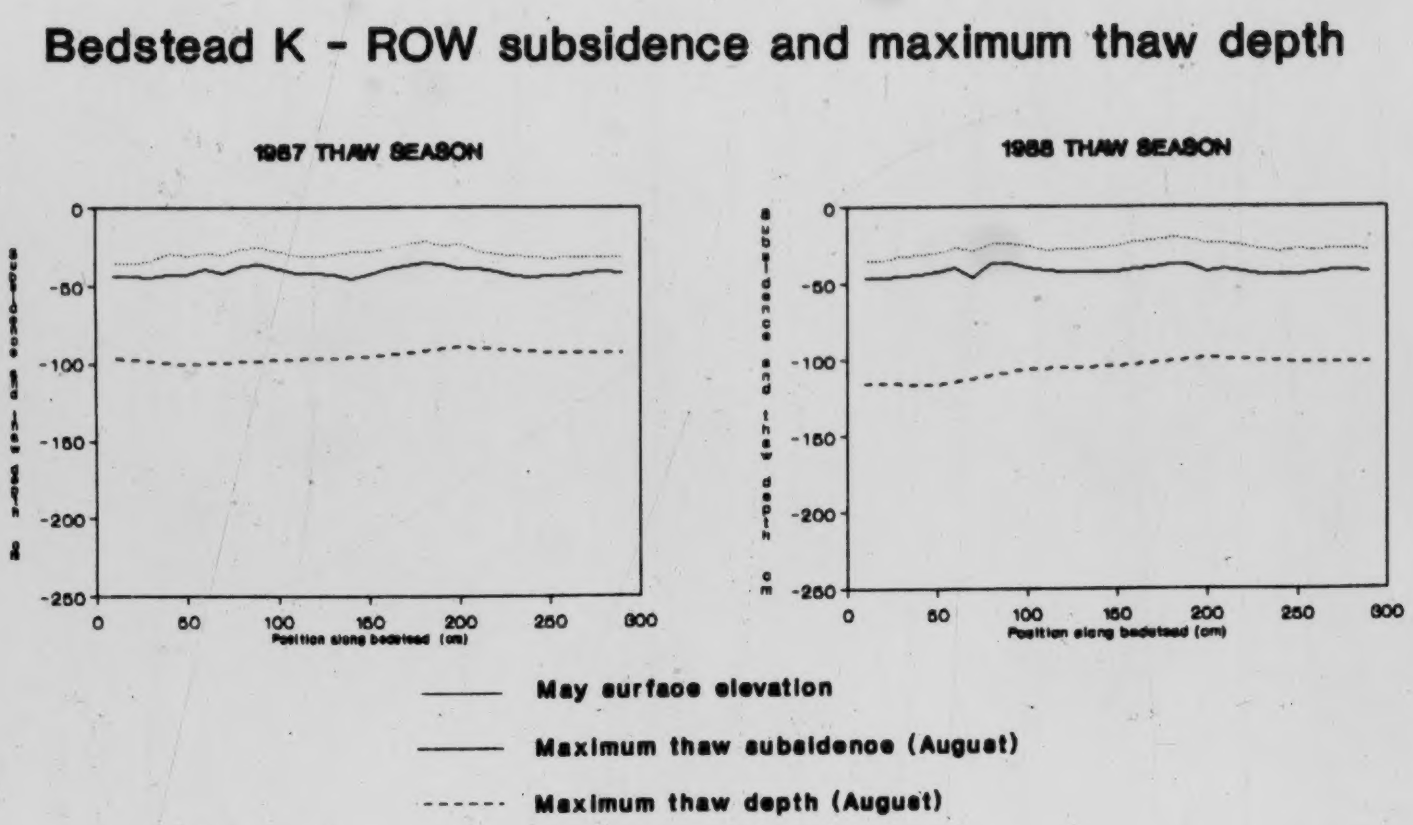


Figure 5.14 Right-of-way bedstead K - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

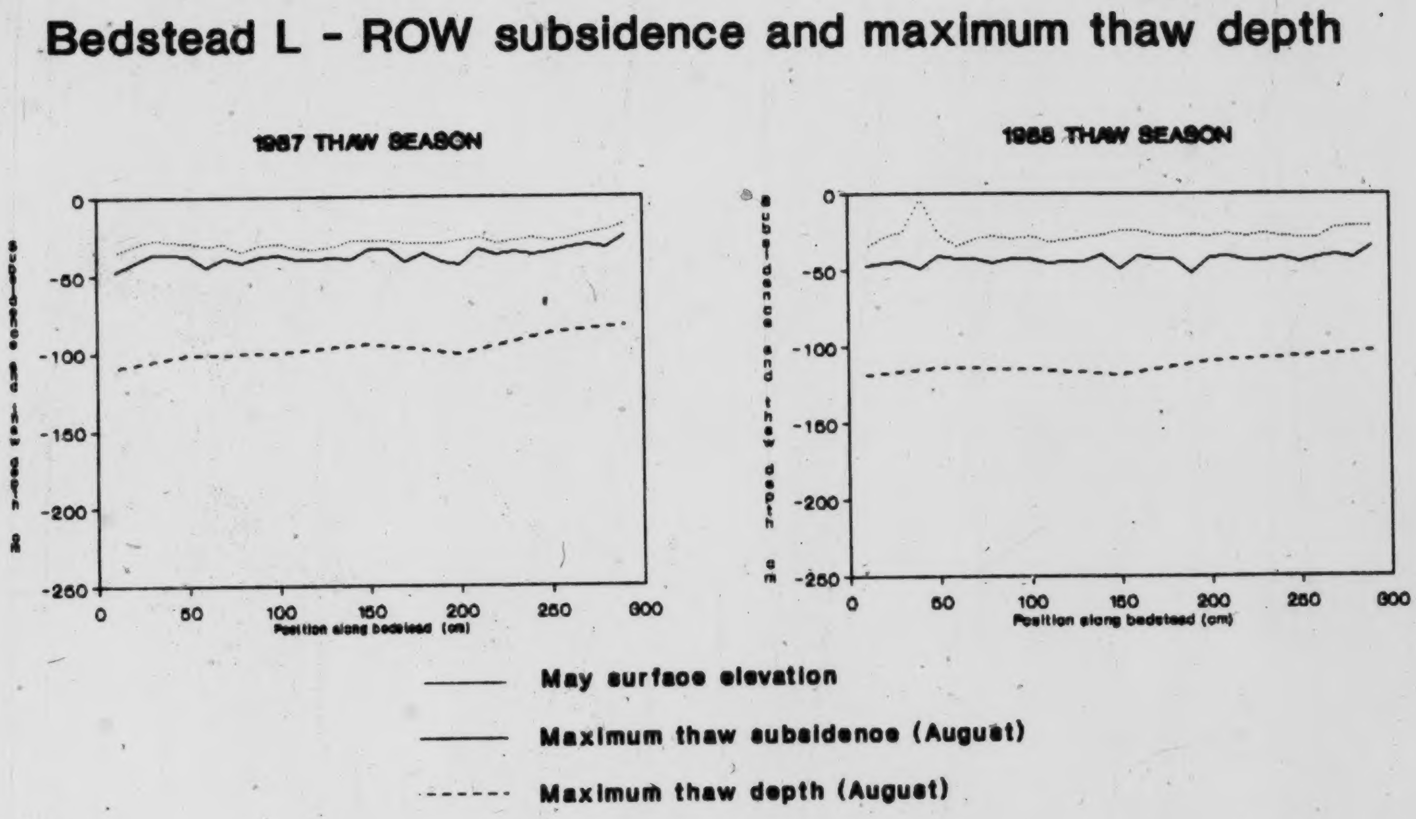


Figure 5.15 Right-of-way bedstead L - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

CONTROL - BEDSTEADS M AND N

The lowest values of thaw subsidence occurred under the undisturbed control conditions. Mean surface settlement during the 1987 monitoring period was 6.18 cm, whereas in the 1988 season the amount of surface lowering almost doubled (12.12 cm). The fact that the 1988 monitoring period was 42 days longer than in 1987 may help to explain this increased value. This is supported by the fact that the thaw subsidence rates remained essentially the same over the two consecutive thaw seasons. The 1988 control subsidence values exceeded those of the highly disturbed trench sites by 32%.

The general lowering of the surface over the thaw season was consistent over the length of the bedsteads, resulting in an end-of-season surface that essentially paralleled the spring surface morphology (Figures 5.16 and 5.17). The seasonal permafrost table also reflected the surface morphology. Mean maximum thaw depth increased slightly (by 10 cm) between 1987 and 1988.

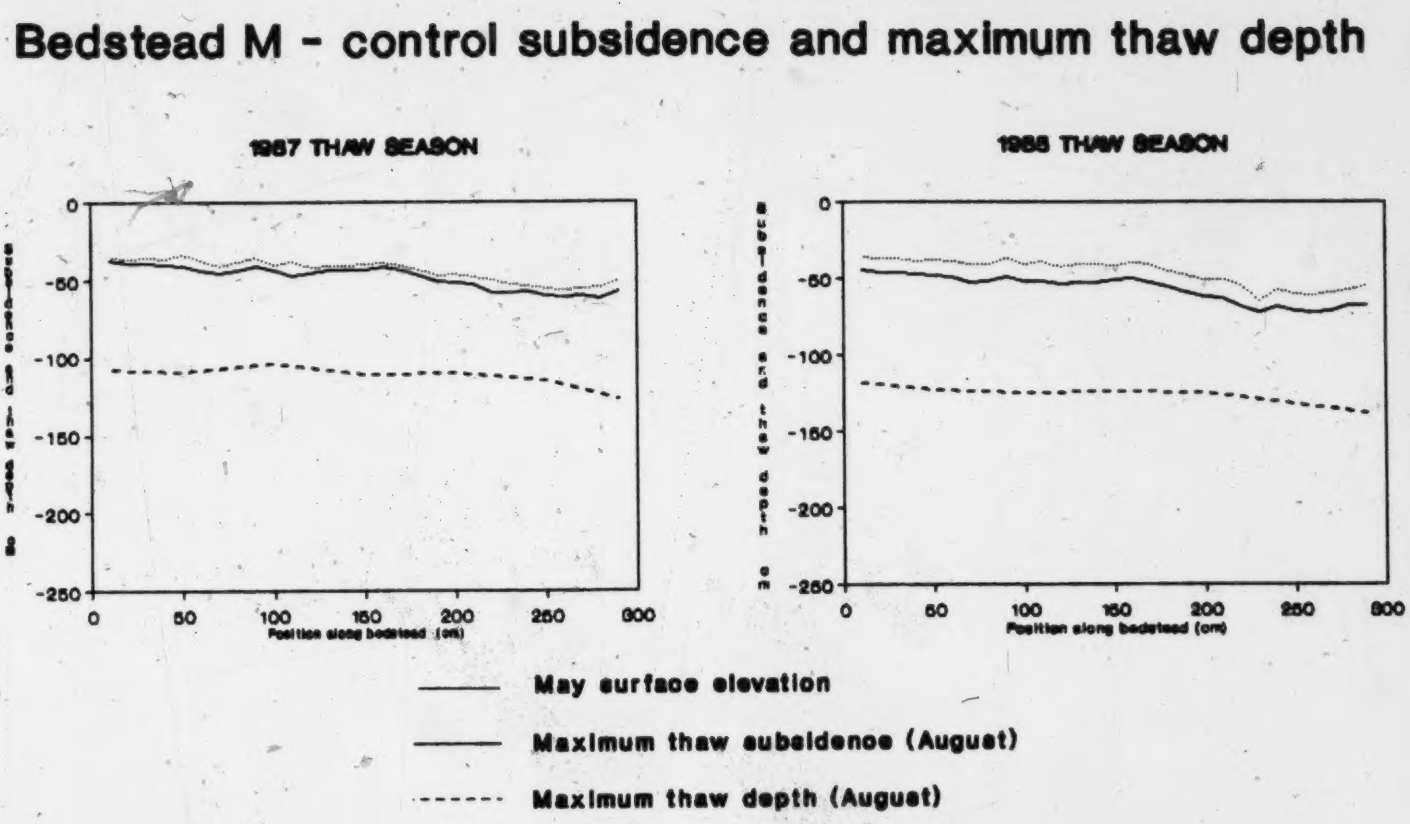


Figure 5.16 Control bedstead M - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

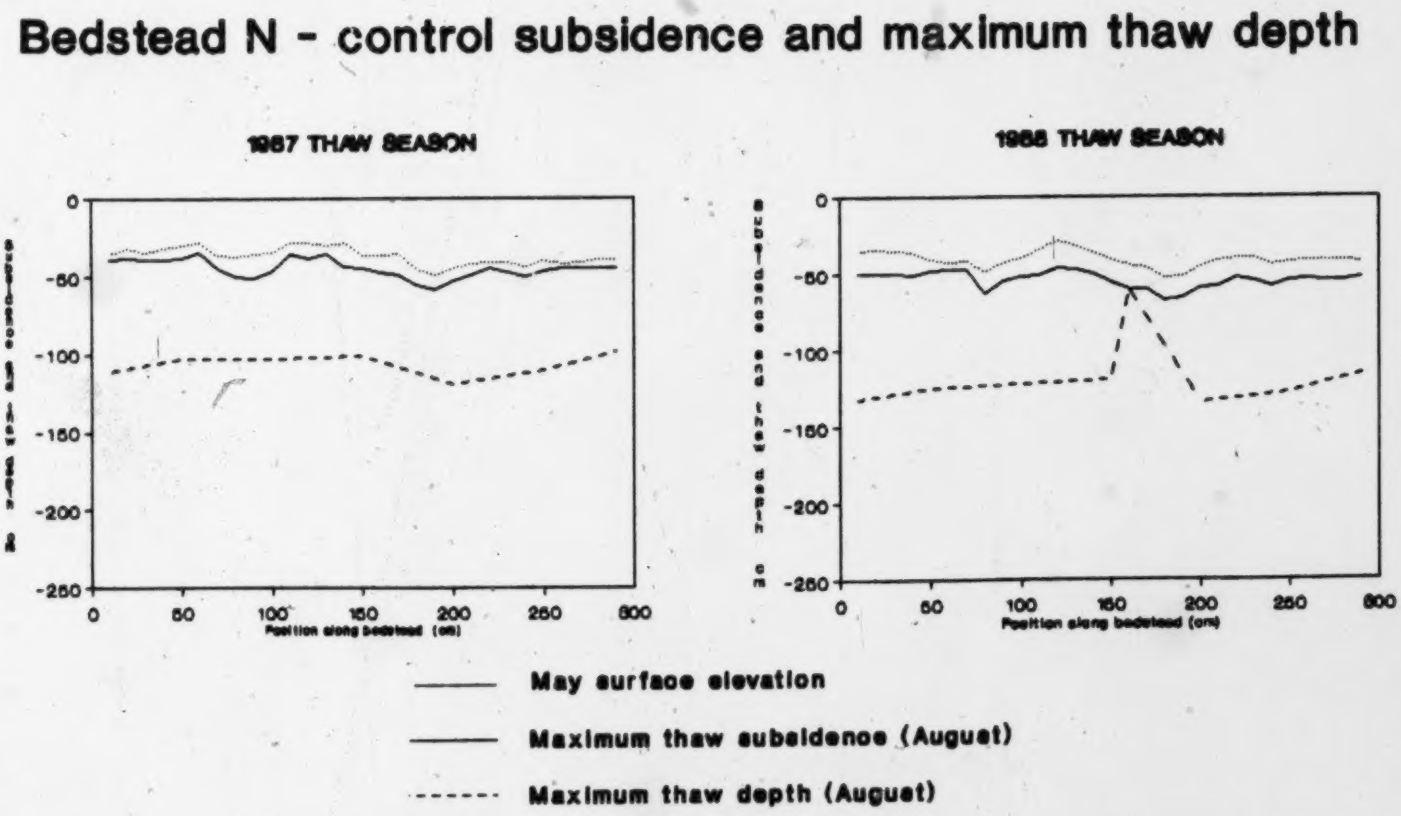


Figure 5.17 Control bedstead N - initial surface topography and maximum thaw subsidence and maximum thaw depth at or near the end of the 1987 and 1988 thaw seasons.

DISCUSSION

TRENCH

The trenched areas had the greatest increase in thaw depth as a result of experiencing the greater severity of disturbance. By the end of the 1988 thaw season, the trench active layer had increased by 57.6 cm (80%) over the 1986 trench thaw depths and 220% over the 1986 control values (based on frost probe transects).

Thermokarst subsidence was maximized under the trench conditions in the first year of observation, with a surface lowering 143% greater than the thaw subsidence occurring within the undisturbed control. In the second year however, there was a dramatic decrease (106%) in the amount of trench subsidence. The thaw depth associated with the trench bedsteads, on the other hand, increased by 30% in 1988.

Studies by Nixon and McRoberts (1973) and Nixon and Ladanyi (1978) have shown that the liberation of excess pore fluids, resulting from the melting of ground ice, is controlled by the rate of movement of the thaw front. The rate of ground surface settlement thus followed a pattern similar to the rate of thaw.

The rapid advance of the thaw front under the trench disturbance conditions suggests that excess pore pressures would likely be generated, particularily as the ice-rich aggradational ice layer melts. The slope of the site, although gradual, provides drainage of the ground ice meltwater away from the thaw plane. This drainage is associated with a change in the volume of the frozen soil. Thaw consolidation and the ice to water phase transition are also integral processes affecting the change in soil volume upon melting. Increased permafrost degradation under the warmer trench soil regime resulted in the progressive thawing of the ice-rich zone during the three thaw seasons. The 1988 mean maximum thaw depths associated with the trench bedsteads was 126.88 cm, well below the zone of maximum ice content. Below 100 cm, the soil moisture contents decreased dramatically to a mean value of 30% at 225 cm, thermokarst subsidence was thus minimized due to the reduced availability of meltwater at greater thaw depths.

The subsurface trench discharge values, ranging between 0.004 and 0.15 l sec^{-1}, demonstrated the underground movement of meltwater as it migrates away from the thaw plane. As the thaw seasons progressed and the thaw front deepened there was a decrease in the subsurface discharge to virtually no flow throughout August. Perhaps water migrating from the deeper thaw front was not captured by the flow barrier and brought to the surface.

The control and the ROW sites were characterized by thermokarst subsidence (downwearing) creating a hummocky irregular terrain. The simulated pipeline trench disturbance, on the other hand, was modified by a combination of thermokarst subsidence and fluvio-thermal erosion processes.

Thermokarst Subsidence Processes

Modification of the ROW 1 trench surface was primarily by thermokarst subsidence and not fluvio-thermal erosion processes. No bedstead monitoring stations were located on this trench therefore observations were generally qualitative. On ROW 1, in 1985, four individual trenched segments were excavated and backfilled. Immediately following these operations the trench surface was generally level with the adjacent right-of-way surface. In the first thaw season following the creation of the trenches, the frost probe measurements indicated an abrupt plunge of the frost table at the margins of the trench. The backfilled sediments underwent considerable subsidence and consolidation during the first two thaw seasons, resulting in the trench surfaces being much lower (up to 60 cm) than the adjacent rights-of-way. These enclosed depressions served to trap water (from snowmelt, precipitation, surface runoff and ground ice meltwater) creating standing pools with up to 10 cm of water throughout the majority of the thaw season. Continual bubbling of water through the trench sediments suggested a subsurface source of water in the Treatment 1 segment.

The standing water served as a sink, absorbing heat during the long hours of heat input from solar radiation

(Harlan, 1974; Linell and Tedrow, 1981). Warmer temperatures at the ground surface result in the acceleration of degradation of the underlying permafrost. This facilitated further thaw subsidence and consolidation (Lawson, 1986; Nelson and Outcalt, 1982). As the trench continued to settle, steep lateral slopes were created along the margins. The lateral expansion of these closed trench depressions into the adjacent, and relatively undisturbed, ROW surface was accomplished by the exposure of the frozen sediments along the trench margins and retrogressive thawing. Zoltai and Woo (1978) describe this process operating in the enlargement of thermokarst ponds. The fact that the mean in-situ water content of the soils was usually greater than its liquid limit suggested that these soils were inherently unstable upon thawing with little shear strength. Subsequent gravitational processes such as micro-slumping and liquefied flow resulted in the deposition of these margin sediments into the bottom of the trench (Plate 5.4). This process continued over the two thaw seasons resulting in the expansion of the original trench width by up to 2 m. The lateral expansion along the trench depressions is reflected in a corresponding expansion of the thaw bulb beneath the trench (Figure 4.2). This suggests that the subsidence and consolidation process will continue for some time yet. Lawson (1982) and McRoberts (1975) suggest that the deposition and accumulation of sediment within troughs will eventually slow the thaw bulb enlargement and thus retard continued surface subsidence.

On level sections of the trench, where subsidence was not intense, surface lowering resulted in depressions filled with shallow water (less than 10 cm deep). Little or no vegetation was re-established on the ROW 1 trench surfaces in 1987, primarily due to the continually saturated condition of the sediments.

Plate 5.4 Example of fluvial undercutting on a micro-scale and the subsequent exposure of the still frozen trench margins to further thawing. Collapse of bank sediments can be seen in the lower right hand corner. Approximate relief between the trench bottom and the adjacent ROW surface is 20 cm (blue pen for scale).

Thermokarst Subsidence and Fluvio-Thermal Erosion Processes

The disruption of the natural surface and/or subsurface movement of water by man's activities or structures such as winter trails, building sites, and in particular linear structures (roads and pipelines) may have serious terrain consequences (Berg and Smith, 1976; Berg et al. 1978; Johnston, 1981; Zoltai and Woo, 1978). The ground thermal regime can be affected to the point where aggravated thawing, surface subsidence and erosion can affect the local environment.

The linear nature of the simulated pipeline trenches (on ROWs 2 and 3) combined with the slope of the site facilitated the interception of surface and subsurface drainage, which runs diagonally across the site (Figure 5.18). ROWs 2 and 3, run north to south across the site and follow the general slope of the surface. The slope, although relatively gentle (2°-3°) was sufficient to promote the channelization of water. Increased subsidence along the trench surface, compared to the adjacent ROW surface, promoted the interception of snowmelt-generated runoff, rain-generated surface runoff and throughflow within the organic mat.

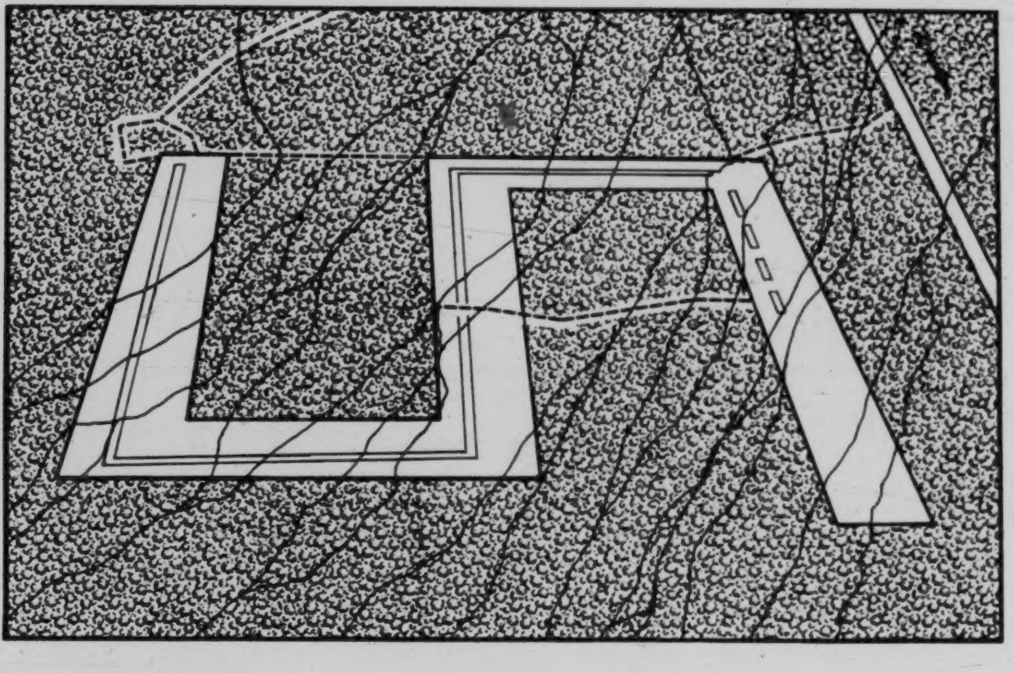


Figure 5.18 Overview of study site showing the location of the sub-parallel surface drainage and seepage lines that run diagonally (SW to NE) across the SEEDS site. Dashed lines represent established foot paths.

Differential subsidence created irregular depressions along the trench in which pools of water collected (Plate 5.5). When surface water increased in velocity during peak snowmelt or intense precipitation events, these formerly isolated depressions became interconnected and drainage developed. Except for periods when discharge down the trench was at a maximum, trench discharge tended to occur along parallel channels running down either side of the trench.

Local meltwater erosion as well as enhanced subsidence are promoted by heat conduction/convection through flowing water particularly during the spring snowmelt period. This period is short, generally lasting about two weeks in early May. The still frozen ground surface acts as an impermeable barrier prohibiting the infiltration of meltwater, thus surface flow (sheetflow and rilling) is initiated (Slaughter and Benson, 1986).

Snow cover remained approximately one week longer in the trench areas than on the adjacent rights-of-way. Early meltwater flow down the trench depressions helped in the ablation of this snow. It has been suggested that because of the high heat storage capacity of water, the presence of water within depressions indicates an excess of thermal energy thereby contributing to thawing of the still frozen ground surface (Nelson and Outcalt, 1982).

Plate 5.5 Differential subsidence on level ground created irregular depressions along the trench in which shallow pools of water collected. North Link, 1986.

As the thaw depth increases with the progression of summer, the moisture storage capacity of the active layer also increases and surface runoff is thus reduced. The increase in air and ground temperatures and the subsequent increase in evapotranspiration also reduces surface runoff (Woo and Steer, 1982; 1983). Post-snowmelt surface discharge values, over the 1987 and 1988 thaw seasons, averaged 0.02 l sec^{-1}. Occasional precipitation events throughout the summer re-activated the surface runoff with maximum discharge values up to 2.67 l sec^{-1}. Discharge following such events lasted for several days and gradually decreased back to baseflow levels.

Woo and Steer (1982, 1983) claim that permafrost regions are most vulnerable to terrain disturbances when surface flow is at a maximum. Surface discharge measurements along the ROW 3 trench during the snowmelt period were often in excess of 4 l sec^{-1} (Plate 5.6). Serious erosion can be common where linear disturbances intercept natural drainage lines. Extensive fluvial and thermal erosion has been observed in association with roads and seismic lines (Kerfoot, 1973; Kurfurst, 1973; Lawson, 1982, 1986), fire breaks (deLeonardis, 1971; Nelson and Outcalt, 1982; Viereck, 1983), and buried pipeline trenches (Burgess and Harry, 1990; Thomas and Ferrel, 1983; Watmore, 1969; Wishart, 1988).

Plate 5.6 Example of trench discharge following the spring snowmelt period. South end of ROW 2 trench at the beginning of the 1987 thaw season.

These studies emphasize the significance of meltwater flow as an effective erosion agent in permafrost-affected terrain. A common denominator in these studies was that a combination of thermal and mechanical slope erosion processes served to continue and aggravate the original terrain disturbance that involved the removal of the vegetation cover and organic mat. Thaw subsidence and consolidation create the original depression while fluvial erosion removes the thawed sediment thereby exposing the underlying frozen soil to thawing and thermal erosion. The saturated sediments offered little resistance to hydraulic erosion by snowmelt and ground-ice melt water.

Because the moisture/ice contents of the frozen soils ($\bar{x}$=57% ice by volume at 40 cm depth) were generally in excess of the liquid limits ($\bar{x}$=38.6, S.D.=8.74), the thawing of the trench sediments produced an unstable sediment that was capable of flowing on a slight incline. Much of the sediment was entrained, either as suspended or bed load, by the flowing water and was transported downslope. The removal of this material exposed the underlying frozen soil to thawing thus creating a self-perpetuating process (Kurfurst, 1973; Lawson, 1982; Strang, 1973). The loss of surface elevation along the upper portions of the trenches (southern end) may therefore be partially attributed to fluvial thermal erosion processes rather than exclusively thaw subsidence and consolidation processes. Sediments were deposited in the form of microcurrent ripples and small bars were observed on the trench floor. Lawson (1982, 1986) suggested that these types of indicators demonstrate the efficacy of flow in the trough depressions for transporting and redistributing sediment.

The sediments were primarily deposited at the northern ends of the trenches (e.g. Bedstead C) where the gradient decreased and surface flow was insufficient. Sediment thicknesses varied considerably ranging up to 10 cm. The partial burial of the 25-cm-high herbivory cages attests to the amount of deposition (Plate 5.7). Over time the insulation provided by these sediments may help to reduce the thaw bulb growth associated with the disturbance and the eventual aggradation of the permafrost table. On ROW 2 flow down the trench was diverted onto the right-of-way approximately halfway down the ROW, thus reducing the erosional and depositional effects in the downslope portion of the trench.

Plate 5.7 Sediment deposition due to gradient decrease at the north end of ROW 3 trench, June 1986 as evidenced by the partial burial of the herbivory cages (25 cm high).

Mackay (1970) suggested that thermokarst subsidence not thermal erosion was the dominant end result of human-induced disturbances in the North. Kerfoot (1973) agreed claiming that the importance of thermokarst fluvial erosion in permafrost environments has been overestimated. His main arguments being that the prevalence of low gradients in the north would limit erosive action and differential ground settlement would preclude the development of integrated drainage and erosion over any appreciable distances. This study, however, shows that even on a relatively gentle slope, and after only three thaw seasons, the intial trench disturbance has been substanially accentuated by the action of flowing water. The significance of such fluvial processes was particularly evident in the ditchline erosion and the subsequent exposure of the IPL pipeline following intensive precipitation and surface runoff (Wishart, 1988). Extensive and expensive remedial measures were required in order to restabilize the ground surface and to ensure the pipeline integrity.

RIGHTS-OF-WAY

The initial disturbance of the ROW involved the clearing of the *Picea mariana* and *Larix laricina* tree canopy as well as the removal of shrubs greater than 0.5 m tall. The short-term effects of this disturbance were the alteration of the ground surface thermal regime and the degradation of the near-surface permafrost. This degradation resulted in the 67% (1987), and the 120% (1988) increase in the seasonal depth of thaw as compared to the undisturbed control thaw depths (based on frost probe transects).

As described in Paper 1, following canopy removal the ROW experiences increases in solar radiation, temperatures, wind speeds, *etc.*. These changes in the microclimate serve to increase the evapotranspiration rates thus resulting in the desiccation of the surface organics. The effective insulation provided by this desiccated organic mat limited the amount of thaw and thus thaw subsidence by reducing the amount of increased soil heat flux (Haag and Bliss, 1974a, 1974b; Smith, 1988).

Compaction of the surface organics and upper soil horizons was intentionally limited in the vicinity of the ROW bedsteads, however, significant compaction did occur on some portions of the rights-of-way as a result of foot traffic and various experimental activities. The partial destruction of the surface organics and the subsequent saturation of these sediments was particularily evident on the South Link as a result of experimental ATV traffic (Plate 5.8) (Evans and Kershaw, 1989). Channelization of surface runoff was evident along the major footpaths where compaction and disruption of the surface vegetation and organic layer promoted increased thaw and subsidence. Increased bulk density and thermal conductivity and the subsequent increase in thaw depth was associated with an increase in thaw subsidence. Similar findings from foot and vehicle traffic disturbance studies were common throughout the Arctic and Subarctic regions (Adam and Hernandez, 1977; Rickard and Brown, 1974; Watmore, 1969). Consolidation of the sediments in many of these situations was the result of compaction rather than the packing of the soil structure upon overburden and suction/drainage pressures.

Differential surface compaction may also be a contributing factor in the differential settlement of the ROW surface creating an irregular or 'hummocky' surface with local relief of up to 50 cm. This irregular settlement may also reflect the variability in the thickness of the insulating organic layer and in the ice contents of the underlying sediments that is typical of the SEEDS site (Evans _et al_., 1988).

Plate 5.8 Compaction of the surface organics and near-surface soil horizons by intentional ATV traffic resulted in the saturation of the sediments. Distribution of seepage channels were made clearly evident by such surface disturbances, South Link - June 1987.

The similar amount of subsidence that occurred over the 1987 and 1988 thaw seasons may be the result of the small, 21% increase in thaw depth over the two years. A point to mention here is that the increase in mean maximum ROW thaw depths associated with the bedsteads was only 12 cm (21%) whereas the more intensive sampling associated with the frost probe transects revealed a 33% increase. The spatial variability that existed in thaw depth suggests that considerable variability also exists in thermokarst subsidence.

The decrease in the ROW moisture content (and implied ice content) in the upper soil horizons associated with the increase in the seasonal depth of thaw influence the amount of subsidence experienced. While the zone of maximum excess ice was located at a depth of 60 to 90 cm, the maximum thaw depths in 1988 were only 67 cm. The maintenance of similar subsidence values over the two thaw seasons may be the result of the thaw depth always being slightly shallower than the ice-rich zone. The melting of the relatively ice-poor (pore and segregated ice) upper soil layers results in a general, but minor, lowering of the ground surface.

The presence of a nearly continous ground cover of moss and lichen, as well as the existence of irregular topography effectively limits or prevents fluvial erosion of the ROW surface. Movement of water is generally accomplished by seepage through the organic layer and near-surface soil horizons. During May and June, water from the melting of snow and the near-surface ground ice migrates through the still shallow active layer. Mean subsurface discharge measurements for this time period ranged between 0.04 and 0.13 l sec^{-1}. As the storage capacity increased with increasing active layer thickness, the subsurface discharge values steadily declined to nil through July and August except following occasional precipitation events. The subsurface flow barriers were only constructed to a depth of approximately 60 to 75 cm thus, eventually, when the mean thaw depth exceeds 75 cm water migrating from the thaw front could potentially be routed under the barrier and not be recorded.

The conditions of low ground ice and inhibited drainage (as suggested by the low subsurface discharge values), associated with the ROW bedsteads, resulted in a limited amount of surface modification. Observations of the entire right-of-way disturbance, however, suggest that substantial spatial variability in local drainage and ground ice content existed and resulted in considerable variation in the response of the terrain surface to the clearing disturbance.

CONTROL

According to the frost probe data the maximum thaw depth of the control sites between 1986 and 1988, increased from 40.3 to 58.9 cm, an increase of 46%. Despite this unexpected increase in the control active layer over the duration of the study, the control sites had significantly shallower thaw depths than the ROW and trench sites in all three years (P<0.0001).

The 6.18 cm (1987) and 12.12 cm (1988) of thaw subsidence that occurred under control conditions may not be related entirely to the normal 9% loss of volume upon the phase change of ice to water associated with the seasonal melting of ground ice within the active layer. Control sites had very high (mean 350%, S.D.=145) near-surface (0 - 45 cm) soil moisture contents, which upon melting, would have resulted in higher subsidence values than would be expected with the phase change of ice to water alone.

The apparent doubling of the thaw subsidence values was likely the result of a substantially longer (42 days) monitoring season in 1988. Given similar subsidence rates in both 1987 and 1988, the total ROW subsidence, if over the same time period, would likely be the same. The similarity in thaw subsidence values and rates was expected since there was no change in the ROW surface and climate conditions over the two thaw seasons.

Thaw depths in both 1987 (63.14 cm) and 1988 (70.7 cm) would have resulted in the melting of ice within the upper portions of the ice-rich aggradational zone (60 and 90 cm) in the control soils. The release of additional water from the melting of this excess ground ice would increase the potential for thermokarst subsidence. The fact that the control subsidence values in the 1988 thaw season exceeded that of the trench sites by 32% supports this theory.

Thaw depths associated with the control bedsteads were considerably (20-25%) greater than those determined by the more intensive frost probe surveys. This was likely the result of the locational requirements of the control bedsteads. The establishment of the bedsteads within the forest sites required an open location with greater than 3 m between trees. The open canopy location of the control bedsteads may create soil thermal regimes more similar to the ROW surface than would be expected under the typically denser forest canopy. Higher mean annual ground temperatures as a result of greater solar radiation, snow cover etc. would explain the thicker than average active layers. Highly variable vegetation and ground cover and substrate conditions (ice content) within the undisturbed control, combined with the low sample size (n=2 bedsteads with 29 measurements each), may also explain the unexpected high thaw depths. An increase in the control sample size would have reduced the odds of randomly selecting two sites with high ground ice content and high thermal-subsidence potential. As the undisturbed control sites were meant to demonstrate the natural processes of seasonal active layer development and annual thaw subsidence, the increases in these variables as recorded at the bedstead sites, was beyond the expected range of normal variability.

The mean thaw rates, based on the delta thaw values between June and September indicated that thaw was most rapid under control conditions in 1987. Caution must be used when interpreting these results due to the observation from the frost probe study that the thaw rate decreases progressively with time, a condition noted by others as well (Jahn, 1985, McRoberts, 1975). Monitoring of the control bedstead thaw depths was not initiated until June 17, 1987 and by that time the rapid early season thaw in the ROW and trench sites had already occurred and subsequent thaw was proceeding at a slower rate. However, soils under the control sites had only just begun thawing and were doing so at the initially high rate. The majority of control thaw for the season had yet to occur.

EFFECT OF THE SOIL ICE CONTENT

The detrimental effects of increased thawing of the permafrost includes the formation of thermokarst terrain. Lawson and Brown (1979) claim that the extent of thermokarst is determined by the intensity of disturbance and the subsequent increase in thaw depth. The degree of permafrost degradation at the SEEDS site was shown to be related to the severity of the original disturbance, however, the correlation between maximum subsidence and maximum thaw depth was not as strong.

The magnitude of subsidence was more directly proportional to the content and distribution of ground ice and the frozen bulk density of the soil (Lawson, 1986; Speer _et al_., 1973). The increasing active layer thickness, as a result of permafrost degradation resulted in the melting of the ground ice. Thermokarst subsidence is generally proportional to the volume of ice in excess of the pore space of the sediment in an unfrozen state (Crory, 1973; Morgenstern and Nixon, 1981; Nixon and McRoberts, 1973). Immediately following the surface disturbances the initial thickening of the active layer and surface subsidence occurred quickly. The fact that in 1987 ROW 2 was experiencing its second thaw season is reflected in the higher subsidence rates associated with the melting of high ice content surface soils (0 - 30 cm). The subsidence values and rates slowed somewhat as the thaw front passed through the zone of lower ice content (30 - 60 cm) that was dominated by pore ice. The maximum amount of subsidence occurred when the thaw front encountered the ice-rich zone of aggradational ice located at a depth of 60 - 90 cm, regardless of the level of disturbance. Beyond this ice-rich zone there was a dramatic decrease in moisture contents and a slowing down of the magnitude of subsidence. The subsidence process at the SEEDS site appears to follow that described for the Norman Wells Pipeline rights-of-way (Burgess, 1988; Burgess and Harry, 1990), where the active phase of topographic changes associated with the pipeline disturbance lasted for 2 to 3 years.

Ice content by volume determinations at the SEEDS site were limited to those associated with bulk density measurements. These samples were all from the Cy and Cz horizons and thus provide little information about ice content from other soil horizons. A more intensive collection of frozen core and frozen bulk density samples, both areally and with depth, would help to determine the potential for thermokarst subsidence as well as defining the potential for differential settlement upon thawing. Post-disturbance measurements of soil moisture/ice content would document the migration, loss and/or addition of moisture within the active layer and would also help to explain the spatial and temporal variations in subsidence. Intensive ground-ice studies are thus an important prerequisite to the knowledgable use and protection of the ground surface (Brown and Grave, 1979, French and Smith, 1980).

CONCLUSIONS

Objective 1

The severity of the disturbance and the subsequent degradation of the near-surface permafrost had a general relationship to the amount of thermokarst subsidence experienced at the site during the first year of observation. Mean maximum thaw depths and maximum subsidence values were greatest under the highly disturbed trench locations. The hand-cleared ROW sites, representing the intermediate level of disturbance, had intermediate thaw depths and subsidence values. Minimum thaw depths and subsidence values were recorded under undisturbed control conditions.

During the 1988 thaw season, the substantial increase in the control thaw depths resulted in unexpectedly high thaw subsidence values. The control unexpectedly experienced the maximum amount of subsidence when compared to the ROW and trench disturbances. The magnitude of subsidence values during the 1988 thaw season demonstrated the importance of the the ground-ice content and its spatial distribution, in particular the position of the aggradational ice layer at the base of the active layer and its relationship to the thaw front.

Objective 2

Numerous short-term degradational processes associated with thermokarst subsidence have resulted in considerable modification of the simulated pipeline trench disturbances. Subsidence and consolidation of the trench sediments allowed for the channelization of surface water and thus promoted both mechanical and fluvio-thermal erosion processes. Gravitational slope processes, on a micro-scale, served to expand the degradation laterally beyond the limits of the original trench disturbance.

The presence of a nearly continuous vegetation/organic mat on the rights-of-way and the control sites, by limiting surface runoff, restricted the terrain disturbance to differential settling of the ground surface and localized ponding.

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CHAPTER 6: GENERAL CONCLUSIONS

Disturbance almost invariably leads to a disruption of the thermal equilibrium of the ground and a subsequent increase in the mean annual depth of thaw. Because disturbances range from the very mildest to the most severe, a continuum also exists in the effects. In the case of the undisturbed control and the hand-cleared ROW, the increase in annual thaw and subsidence was relatively minor, expressed as irregular topography resulting from differential thermokarst subsidence. The most extensive modifications occurred on the highly disturbed trench site. Permafrost degradation and thermokarst processes were maximized under these conditions.

While the terrain response under the control and ROW conditions was generally localized, degradation of the permafrost under trench conditions also induced a number of other thermokarst-related processes such as micro-scale slope failure and the removal of surface materials by mechanical and/or fluvio-thermal erosion which extended the limits of damage beyond the original disturbance. Significant terrain impact was also noted in association with unintentional disturbances such as footpaths.

The interactions of permafrost and environmental factors of climate and terrain are varied and very complex. No simple correlation of these variables exists to describe all conditions and all locations (Linell and Tedrow, 1981). Even a slight change in one factor will produce a change in one or more other factors, in some cases creating the circular exacerbating chain of events noted by many researchers (Hegginbottom, 1973; Kurfurst, 1973; Mackay, 1970). Lawsons' flow charts (1982, 1986) illustrate the typical sequences of processes and terrain responses from initial surface disturbance to eventual thermal equilibrium and terrain stabilization. Those processes and responses that have taken place as a result of human-disturbance at the SEEDS site are illustrated in Figure 6.1.

Thermal stabilization of these disturbances will only be attained following physical stabilization and revegetation (Mackay, 1970; Lawson, 1986; Wishart, 1988). How soon thermal equilibrium occurs depends on the extent of the original disturbance and the extent of continuing degradational processes. According to Lawson (1986) minimally disturbed areas such as the rights-of-way may attain stability within 5 to 10 years while the the highly disturbed trench sites that were subsequently modified by gravitational slope processes, and mechanical and fluvio-thermal erosion may take over 30 years. Linell (1973) reported continuing permafrost degradation under a cleared area near Fairbanks, Alaska, 26 years following disturbance. A major conclusion of this and other disturbance research is the need to preserve the integrity of the insulating vegetation and organic mat. Viereck (1982) considers that the re-establishment of a moss

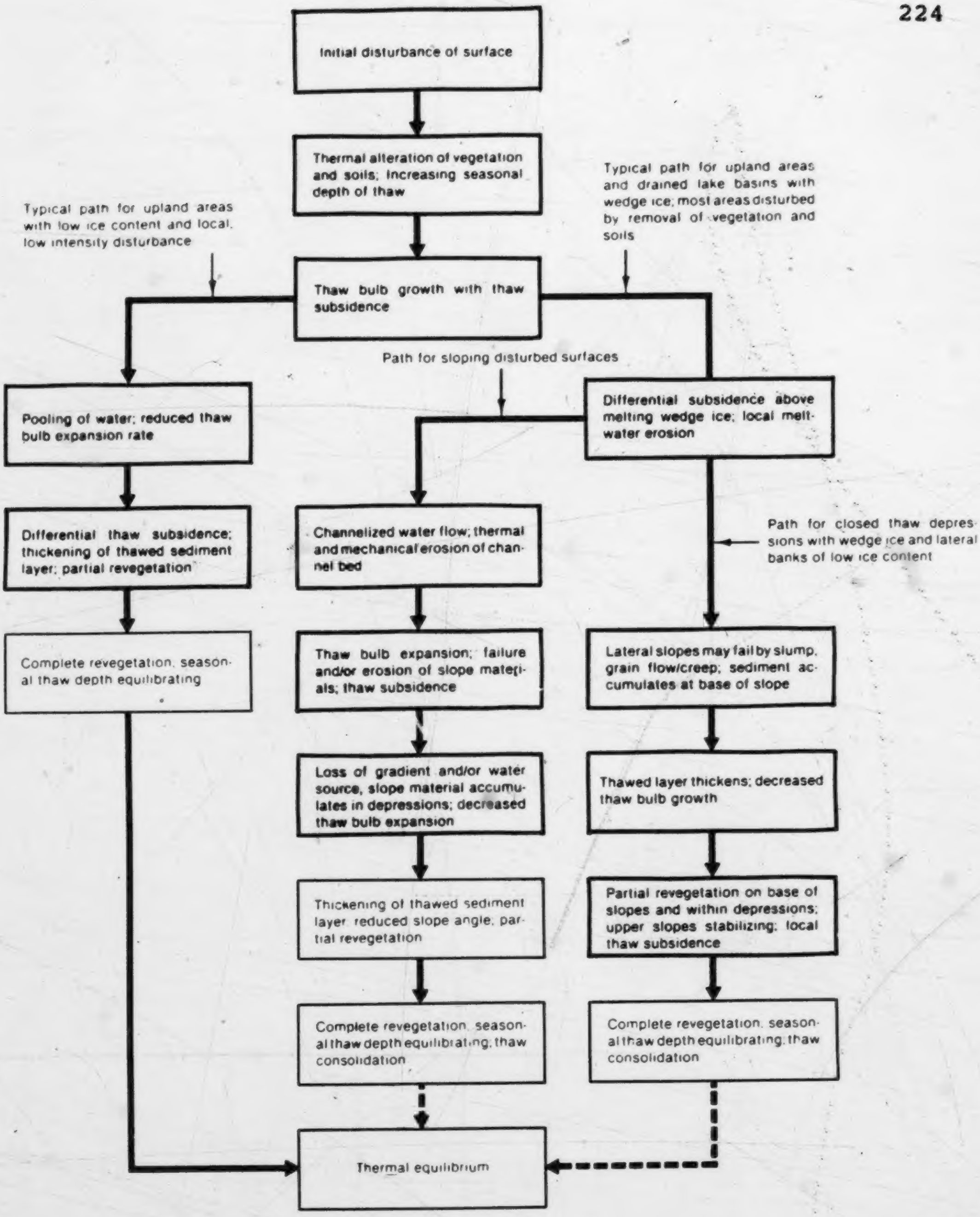
Initial disturbance of surface
Thermal alteration of vegetation and soils; increasing seasonal depth of thaw
Typical path for upland areas with low ice content and local, low intensity disturbance
Typical path for upland areas and drained lake basins with wedge ice; most areas disturbed by removal of vegetation and soils
Thaw bulb growth with thaw subsidence
Path for sloping disturbed surfaces
Pooling of water; reduced thaw bulb expansion rate
Differential subsidence above melting wedge ice; local melt-water erosion
Differential thaw subsidence; thickening of thawed sediment layer; partial revegetation
Channelized water flow; thermal and mechanical erosion of channel bed
Path for closed thaw depressions with wedge ice and lateral banks of low ice content
Complete revegetation, seasonal thaw depth equilibrating
Thaw bulb expansion; failure and/or erosion of slope materials; thaw subsidence
Lateral slopes may fail by slump, grain flow/creep; sediment accumulates at base of slope
Loss of gradient and/or water source, slope material accumulates in depressions; decreased thaw bulb expansion
Thawed layer thickens; decreased thaw bulb growth
Thickening of thawed sediment layer, reduced slope angle, partial revegetation
Partial revegetation on base of slopes and within depressions; upper slopes stabilizing; local thaw subsidence
Complete revegetation, seasonal thaw depth equilibrating; thaw consolidation
Complete revegetation, seasonal thaw depth equilibrating; thaw consolidation
Thermal equilibrium

Figure 6.1 Lawsons (1986) schematic process-response flow chart illustrating the common sequence of processes that resulted surface modification. Shaded boxes indicate which portions of the sequence have been partially or wholely completed at the SEEDS site as of September 1988.

cover and the build-up of the organic layer is the primary means of minimizing thaw depths and stabilizing the surface following disturbance. This may take as long as 75 years.

Heginbottom and Kurfurst (1973) ranked the Norman Wells area as being moderately to highly sensitive to terrain disturbance with its generally high ground-ice contents, thaw susceptible glaciofluvial sediments, high subsidence values, and poor to low slope stability. Burgess and Harry (1990) suggest that this region is also one of the most difficult in terms of fluvial and thermal erosion if the ground cover is highly disturbed. The Mackenzie Valley, unfortunately, is also the major potential transport corridor for future natural gas and oil pipelines and is likely to undergo detrimental terrain effects as a result. Anthropogenic terrain disturbance is likely to be exacerbated by climatic change. The implications of regional climate warming scenarios must be addressed in future environmental protection plans.

The problems of terrain disturbance in permafrost regions can only be solved through the prediction of permafrost changes and the subsequent degradation processes in response to human disturbance. Unfortunately the considerable spatial variability and complexity of northern ecosystems makes it very difficult to make generalizations concerning the effects of surface disturbance over any distance (Webber, 1983). To date, the majority of terrain process-response studies have taken a site-specific approach. The continued integration of multi-disciplinary research, however, may lead eventually to the development of general principles and management techniques for the prediction of potential impact and the minimization of of the detrimental effects of northern land use and development.

Through both the planned and inadvertent effects of human disturbance, future northern development activities will continue to place man in the role as a geomorphic agent, affecting landscape processes and forms.

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